CONDITION-BASED MAINTENANCE: INNOVATION IN BUILDING MAINTENANCE MANAGEMENT

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STUDENT DECLARATION

I confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Ruhul Afizullah Amin

TO MY FATHER, AFIZ ULLAH

"If I have seen further it is by standing on the shoulders of giants"

SIR ISAAC NEWTON (1675)

ABSTRACT

Maintenance is a continuous process implemented by Facilities Management (FM) providers as one their core competences to effectively manage and maintain critical assets throughout the whole life of a building and prevent downtime of essential systems.

Maintenance actions are usually categorised into two main streams: corrective (CM) and precautionary (PM). In CM equipment is repaired after a failure occurs (i.e. reactively). In contrast, PM is applied based on a fixed-time or age-schedule (i.e. preventive). However, a subdivision of PM that is widely discussed in literature, yet rarely implemented in practice within FM, is Condition-based Maintenance (CBM), which enables maintenance to be applied predictively.

CBM exploits the operating condition of equipment to predict a failure occurrence, thus preventing any unexpected downtime and reducing maintenance cost by avoiding unnecessary preventive actions. The underlining theory of CBM is based on the belief that 99 per cent of equipment will evidence some sort of indicators prior to failure. Therefore, it is possible to identify the fault, determine the cause and establish the severity and longevity of the equipment's optimum life through monitoring and evaluating data collected through various techniques.

Nevertheless, although the theoretical foundations of CBM are relevant to building maintenance management, such data and technology-focused strategies are seldom considered to be a viable and feasible option within the FM strategy. Therefore, this thesis details a mixed-methods, action research project undertaken within this industry sector, which has been significantly suppressed of innovative contributions. The study investigates the viability, practicality and impact of implementing an innovative CBM focused maintenance framework that is inclusive of real-time vibration analysis and enhanced with statistical data analysis.

The CBM framework is demonstrated to be economically viable, technically feasible and complimentary to the inadequacies of the existing time-based regime. The framework adds value to the buildings maintenance management objectives.

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Publications and Key Presentations arising from this Thesis

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1 INTRODUCTION

This introduction firstly outlines the problem area of this research and describes the contextual setting along with background research foundations. Secondly, it defines the main aims and research questions. Finally, it concludes with an overview of the thesis structure and chapter synopsis.

1.1 PROBLEM AREA

Building maintenance management is generally considered as a neglected area of the built environment that has been significantly supressed of innovative contributions towards the management service delivery (RICS 2009). Consequently, whilst the theoretical foundations and relevance of technology focused and data motivated maintenance strategies are evident within building services engineering, it is seldom considered as alternatives to the prevalent time-based maintenance programmes, as a result the destitution of innovative methodologies continues within the Facilities Management (FM) building maintenance strategy. Furthermore, although the life expectancy and maintenance requirements of individual mechanical and electrical components within building services can be a diverse and complex operation, proactive actions such as continuous monitoring, examination and replacement of building service systems, components (and sub-components) can be undertaken to not only ensure optimised operations but also to reduce the probability of breakdowns and performance derogation.

Therefore, such proactive management contributes towards the availability, reliability and maintainability (ARM) of equipment (asset), which are essential considerations throughout the whole lifecycle of any asset. Moreover, while asset design is significantly linked to ARM, regardless of design over time deterioration will occur as a result of real environment operation stress and/or load (Jardine et al. 2006). Consequently, an effective way to assure a satisfactory level of performance consistency during the useful life of a physical asset, reduce risk and the eventuality of unexpected failures (which has a direct effect on efficiency), is to perform maintenance (Martin 1994, Jardine, et al. 2006).

Definitions of maintenance emphasise that it is *"a set of activities or tasks used to restore an item to a state in which it can perform its designated functions"* (Dhillon, 2002; Tinga 2010; Ahmad & Kamaruddin 2012). Similarly, the British Standard 3811 (1993) definition stresses *'actions'* (technical and administrative) that are undertaken to *'retain'* in anticipation of failure and *'restore'* after failure. Moreover, maintenance is an activity recommended, and often contractually required by Original Equipment Manufacturer (OEM) to not only ensure validity of warranty, but also to continuously safeguard operating parameters within health and safety thresholds.

Due to the current construction industry pressures for ‘better quality for less’, companies strive to be more proactive (in cost reduction and efficiency) across all the business activities, including asset maintenance. Moreover, there is general consensus that implementing an efficient and effective maintenance approach can increase an organisations production capacity and more importantly it can minimise unexpected asset failures to zero (Al-Najjar & Alsyouf 2004).

Furthermore, continuous maintenance application not only reduces risk and actual downtime caused by unexpected failures, but also reduces the associated energy usage whilst maximizing performance and asset life (Shin & Jun 2015; Jardine et al. 2006; Ahmad & Kamaruddin 2012; Saidur 2010). Therefore, a successfully established maintenance strategy is expected to harmoniously integrate with the wider operations and service delivery mission statement in order to support, compliment and be aligned with the corporate strategy of the core business (RICS, 2009; Pitt et al., 2006).

As a result, maintenance strategies can be generally categorised into Corrective Maintenance (CM) used to restore*,* and Precautionary Maintenance (PM) applied to retain (Ahmad and Kamaruddin, 2012). CM strategy (also referred to as *‘reactive’* or *‘run-to-failure’*) is applied at the time when the asset requires restoration (to be repaired or replaced) (Blanchard et al., 1995; Martin, 1994). Despite its frequent use within some industries, this maintenance technique results in high levels of machine downtime that causes production loss and significantly increases risk and costs associated with unexpected failure (Al-Najjar, 2012; Ahmad and Kamaruddin, 2012).

In contrast, the objective of PM is to reduce risk of failures and avoid the cost associated with a failed asset (Veldman, et al. 2011a; Ahmad and Kamaruddin, 2012). PM is undertaken based on a fixed time or age schedule (usually in-line with OEM and/or industry best practice recommendations) and tackles the problem of equipment failure prior to its failure occurrence. Using proactive principles, this strategy aims to reduce the failure rate or its frequency, at the same time allowing for better product quality and reduction of failure costs (Martin, 1994: Ahmad and Kamaruddin, 2012). However, despite the potential benefits and opportunities, the practical necessity and effectiveness of the most commonly applied maintenance strategies are constantly questioned in the literature and industry.

For example, maintenance interventions within the built environment continue to be perceived as *‘necessary evil’* that are resource intensive and generically scheduled *‘actions’* based on age or time in order to ‘*restore’* or *‘retain’* from failures, although the maintenance requirements of individual assets are diverse and complex (Tam et al., 2006). Moreover, Amari et al., (2006) investigated multiple industries to conclude that age related failures account for only 15 to 20% of all equipment failures. The remaining 80 to 85% of failures is due to random events, suggesting that the popular implementation of time or age based PM is not adequate in practise.

In response to this, since the 1960s the integrated attitude towards maintenance has been evolving. Driven by the continuous development of global markets and industry requirement of dependable and cost-effective service delivery systems, and aided by the advancement of technologies, sensors and data analysis, there have been dramatic evolutions of innovative condition monitoring and data-driven maintenance functions over the last few decades (Holmberg, et al., 2010: Ahmad and Kamaruddin, 2012).

The core goal of these data-centric technology driven initiatives is to inform and support the ARM considerations of assets through enabling a more integrated, efficient and effective maintenance strategy. One of the ambassadors of such ascendancy is predictive maintenance using Condition Based Maintenance (CBM).

The CBM maintenance policy is a subdivision of PM and part of the Reliability Centred Maintenance (RCM) concept, which exploits the operating condition of equipment to predict a failure occurrence thus prevent any unexpected downtime and reduce maintenance cost by avoiding unnecessary preventive actions. Moreover, CBM is based on the assumption that every asset deteriorates and is subjected to complete or partial failure. It is delivered using technologies that aim to analyse the collected data in order to detect the onset of fault and ensure that appropriate action is taken to delay or prevent the breakdown, consequently improving reliability and decreasing risk of failure. CBM is known to use various parameters such as temperature, acoustic emission, vibration or flow to monitor condition of the equipment (Veldman, et al. 2011a).

These measurement techniques are supported by a wide range of ISO standards, including *'Condition Monitoring and Diagnostics of machines – General Guidelines'* (ISO 17359:2011) which provides 27 different condition monitoring and performance considerations (see Appendix I). The data collected based on these parameters indicate the performance, integrity, asset health and allow for proactive, informed scheduling time-consuming correction actions (IAEA, 2007)

The CBM methodology has not only emerged but also evolved in the last decade, as a result it has been deployed to different extents by industries. For example, whilst these advancements have been theoretically tested, and practically imbedded in some industries (such as aviation, processing and wind power) to be aligned in harmony and to compliment the corporate strategy while reducing risk of asset failure, others such as the built environment still fail to practically embrace the full potential by choosing to continue practicing old fashioned second generation strategies with ominous consequences towards the management of reliability, safety, risk and cost.

Therefore, the proposed research uses existing online vibration analysis technologies to implement condition monitoring and statistical data analysis on operational building assets in order to establish the impacts of a third-generation maintenance policy that combines CBM techniques (which support predictive actions) in conjunction with time-based preventive actions with the overall goal to inform decision-making relating to asset health conditions, operations and maintenance needs. Consequently, assisting the transition from Planned PM (PPM) practices to condition monitoring data-driven CBM.

1.2 CONTEXT AND SCENE SETTING

The theoretical conceptualisation and operationalisation of data, technology and its symbiotic relationship with the maintenance and engineering sector is evident in many industries with high value assets. For example, aircraft performance knowledge is optimised through advanced statistical analyses of in-service performance and lifecycle data, which is subsequently applied to maintenance programmes to identify the optimum maintenance intervals thus *'ensure safe, reliable, and cost-effective airplane performance'* as demonstrated by Boeings Statistical Analysis for Scheduled Maintenance Optimisation (SASMO) tool (McLoughlin et al, 2011).

Likewise, the international effort into renewable energy has resulted in a dramatic rise of offshore wind farms with the maintenance expeditions usually requiring the use of ships and helicopters for accessibility. Moreover, replacement of critical components such as rotor blades, gearboxes and generators can be up to twenty per cent of the price of a new turbine. Therefore, remote real-time condition monitoring and data analytics is commonly applied to ensure economies of scale and achievement of design life through the goal of minimum overhauls and reducing risk of unexpected failures (Børresen, 2011). Similarly, the modern car records and calculates thousands of parameters and data points to enable health monitoring, servicing and proactive decisions making of key components such as engine, oil, tyres, filters etc. (Holloway, 2013).

Buildings have commonalities with aircrafts, wind turbines and automobiles. Building assets operate in complex data capture environments with a requirement to manage and maintain critical assets over long periods. Therefore, safety, reliability and cost-effectiveness have always been essential features in the operation of critical building assets. Consequently maintenance of engineering services is a continuous process implemented by FM providers with the core goals of improving reliability through reducing risk of unexpected failures, maximising efficiency while reducing the associated energy usage and increasing the asset life (Ahmad and Kamaruddin, 2012).

The vision to successfully achieve these goals results in billions of pounds being spent annually on maintenance of non-domestic facilities in order to prevent downtime of critical systems. This is particularly relevant to buildings with critical environment such as hospitals and government defence buildings where service disruption generates greater risks throughout all supply chains (BSRIA, 2013).

The built environment's complex supply chains incorporate designing, constructing, operating and maintaining of buildings and infrastructure assets. This diverse construction industry contributes £90 billion gross added value to the UK economy and accounts for 3 million jobs (10% of total UK employment) in over 280,000 businesses.

More recently, the importance to the economy is further emphasised in 'Construction 2025', which is a collaborative strategy by government and industry, setting out the future vision of the industry with a forecast that *'the global construction market will grow by over 70% by 2025'* (HM Government, 2013).

Moreover, in the specific context of building maintenance, CIBSE (2008) conservatively estimated the annual business value of maintenance within the UK to be over £7 billion and with the forecast and visions set out in 'Construction 2025', organisations are starting to comprehend the importance of effective long-term maintenance and management of buildings services.

Nevertheless, the design and construction phases in this rapidly expanding market generally focus on achieving *'value for money'* with minimal whole life considerations, as a result the concept of building maintainability often becomes relevant after construction (RICS, 2009). Yet, the significant relationship between construction and maintenance can be observed through finance, quality and time, therefore value engineering during construction can drastically increase consequential long-term maintainability risk. For example, the ratio of construction capital to maintenance costs can be as much as 1:5 (RICS, 2009). As a result, considering maintenance as a significant factor in the whole life of buildings is essential.

While facilities managers within industry are increasingly accepting that maintenance is not just a *'necessary evil'* cost but can actually generate a profit (Alsyouf, 2007; Veldman, et al., 2011a), there is a significant deficiency of implementing technologies and alternative methodologies to not only validate the viability and applicability of optimisation, but also to develop evidence based tools that enable management decision making at all stages of building lifecycle.

1.3 BACKGROUND RESEARCH

The research project undertaken by the author during the MRes VEIV (virtual environments, imaging and visualisation) programme placed the foundations for the project detailed in this thesis. The research was disseminated in Amin and Pitt (2014).

1.3.1 BACKGROUND RESEARCH: AIM

The aim of the MRes research was to establish the effectiveness of a PPM schedule using condition monitoring to identify the key detectable faults, and ascertain the role of Supply Chain Management in adopting CBM.

1.3.2 BACKGROUND RESEARCH: DESIGN OVERVIEW

An industry renowned hand-held CBM tool was procured from a third-party supplier and utilised on the critical rotary site equipment. This tool required manual data collection using a handheld device. Moreover, the solution utilised vibration analysis for some of the key detectable faults discussed in the literature (namely misalignment, looseness and imbalance). Additionally, it was inclusive of the most recent version of Shock Pulse Method technique (SPM) for detailed bearing analysis. The 83 critical assets in scope were installed with monitoring equipment to provide a total of 383 fault detection and visualisation points.

For the purpose of answering the set research questions in most comprehensive manner, logic of triangulation was adopted through selecting a mixture of qualitative and quantitative research techniques. Quantitative data was collected using the handheld device as per the measurement locations. For qualitative data collection, the researcher firstly carried out a thorough review of the equipment’s maintenance and breakdown records and secondly used unstructured interviews technique to obtain the staff perceptions on the new CBM solution as well as the direct observation to gain an overview of the managerial processes influencing the project.

1.3.3 BACKGROUND RESEARCH: KEY FINDINGS

The background study explored the use of hand-held CBM tools on operational building assets to diagnose common mechanical faults caused by vibration. Focusing on managerial and operational barriers and success factors, it specifically sets out to investigate a total of thirty-one centrifugal pumps and associated motors in order to establish the extent to which vibration induced faults can be identified and diagnosed through the use of vibration analysis even though routine Planned Preventative Maintenance (PPM) is applied on the assets. The key findings were as follows:

1. Through Vibration Analysis and SPM it is possible to detect and diagnose the investigated mechanical faults on operational assets within building services environment.

2. Although the investigated assets were subject to a PPM programme, 48% of assets had or more of the investigated faults. More specifically, 29% (of 48%) of these faulty assets had '*reduced operating condition'* (amber faults) and 19% had red faults indicating *'bad operating condition'* due to harmful levels of vibration (against ISO thresholds).

3. There are numerous managerial and operational barriers to endorsing these CBM techniques, mainly consequent of the manual data collection procedures via handheld device and susceptibility to human errors.

4. PPM schedules based on original equipment manufacturers recommendations and SFG20 standards best practice is not sufficient at completely eliminating the investigated mechanical faults, thus CBM techniques should be utilised in conjunction to compensate.

5. Staff training to analyse complex and effective supply chain management are the two evident managerial themes identified as key success factors in CBM implementation.

However, the background research was a short-term pilot project that utilised a hand-held data collection tool, which required significant human input and setup before the data could be collected. Consequently, the data collection was time consuming and susceptible to human errors. Furthermore, the project was conducted in isolation of the existing maintenance strategy. Therefore, further research is necessary to demonstrate the practicality and viability impacts of a data driven, online CBM solution (without human input for data collection) that is inclusive of building maintenance management considerations and integrated into the existing business processes and systems.

1.4 RESEARCH QUESTIONS, AIMS AND OBJECTIVES

Through transferring and implementing existing technologies into an innovation deprived research area, this study is expected to yield an original contribution to knowledge and to improve our understanding in the field of building operations and maintenance management decision-making.

1.4.1 RESEARCH AIM

The aim of this thesis is to develop the background research by investigating the practicality, viability and impacts of implementing a data driven CBM framework using online vibration analysis in a building maintenance context.

1.4.2 RESEARCH QUESTIONS AND OBJECTIVES

Accordingly, this thesis aims to answer the following research question:

1. What are the impacts of implementing Condition-based maintenance policies in a buildings maintenance context?

Furthermore, to comprehensively achieve the aim of the thesis and support the main research question, the following sub-questions have been developed for investigation:

- 1.1. What are the costs, savings and opportunities of implementing CBM?
- 1.2. What effect does incorporating real-time vibration analysis have on an existing time-based maintenance regime?
- 1.3. What statistical association do plantroom temperatures, relative humidity and asset energy consumption have on the occurrence of faults?

Therefore, the objectives of this thesis are as follows:

1. Undertake a feasibility study to determine key costs, savings and potential opportunities of implementing predictive maintenance (online vibration condition monitoring).
2. Implement online vibration monitoring on critical rotary building assets to establish viability and practicality of predictive maintenance.
3. Collect and statistically analyse data relating to:
    a. Hours of operations, in order to provide insight into the operations strategy and inform maintenance and life cycle decision.
    b. Consumption of electricity, in order to establish whether an association between fault and higher consumption exists.
    c. Atmospheric temperature and humidity, in order to ascertain the environment within which the assets operate.

1.4.3 DEMARCATION

This research focuses on the implementation of condition monitoring and maintenance on rotary building HVAC assets (i.e. centrifugal pumps and air handling unit fans, as well as the associated motors). It will investigate the practicality and viability of implementation a CBM methodology that utilises real-time vibration monitoring. Moreover it will establish the impact of amalgamating condition data with statistical analysis of key operating parameters, energy consumption and environmental sensor data to enable proactive maintenance decision-making.

The concepts of mechanical fault diagnosis and prognosis are important features of CBM (Schwabcher 2005; Jardine et al., 2006; Veldman et al., 2011a; Ahmad and Kamaruddin, 2012). The objective of fault diagnosis (triggered after a specific measurement shows a potential problem) is fault detection, isolation and subsequently fault identification (Jardine et al., 2006). Prognosis on the other hand, predicts the fault before it occurs (by estimating the Remaining Useful Life (RUL)) and can be defined as the process of *"detecting the precursors of a failure, and predicting how much time remains before a likely failure"* (Schwabcher 2005, page 1).

This study will focus on fault detection and diagnosis within an operational building environment with a goal of reducing the risk of asset failure through data analysis, and will not address prognosis. The principal focus will be to establish the impact of implementing CBM technologies and statistical data analysis in conjunction with preventive maintenance. Fundamentally, the research will be based on data relating to key asset operating parameters, mechanical vibrations and the environmental conditions (i.e. temperature and humidity).

Furthermore, it sets out to combine condition monitoring data analysis with operational and energy data with the goal of developing a maintenance management tool that enables informed predictive decision-making in the context of building asset maintenance and operation.

1.5 METHODOLOGICAL OVERVIEW

The size and practical scope of the research project detailed in this thesis is unprecedented both in the literature and within industry in this domain. As a result the nature of the research design is a combination of exploratory and descriptive, developed through an iterative action research process based on an academia and industry Engineering Doctorate (EngD) partnership.

To achieve the main aim of the research, the design strategy contemplated properties including the research field, the nature of research topic itself, as well as the pre-existing methodological guidance available in the selection of the suitable methodology surveyed within international standards and most relevant literatures. For example, the CBM execution model identified in Jardine et al., (2006) and further developed in Veldman et al., (2011) is considered within the general research framework design and practical data acquisition and processing (see Chapter 6).

Therefore, a mixed-method research design is adopted that is supported on the collaborative action research platform. This unique research design enables effective amalgamation of both quantitative and qualitative approaches with the flexibility of incorporating the numerous research instruments for data collection and iterative intellectual scrutiny (Amaratunga et al., 2002). Additionally, the selected methodology will enable casual inferences through opportunities to observe data convergence or divergence of evolving propositions, thus potentially increasing the validity and reliability of the associated data.

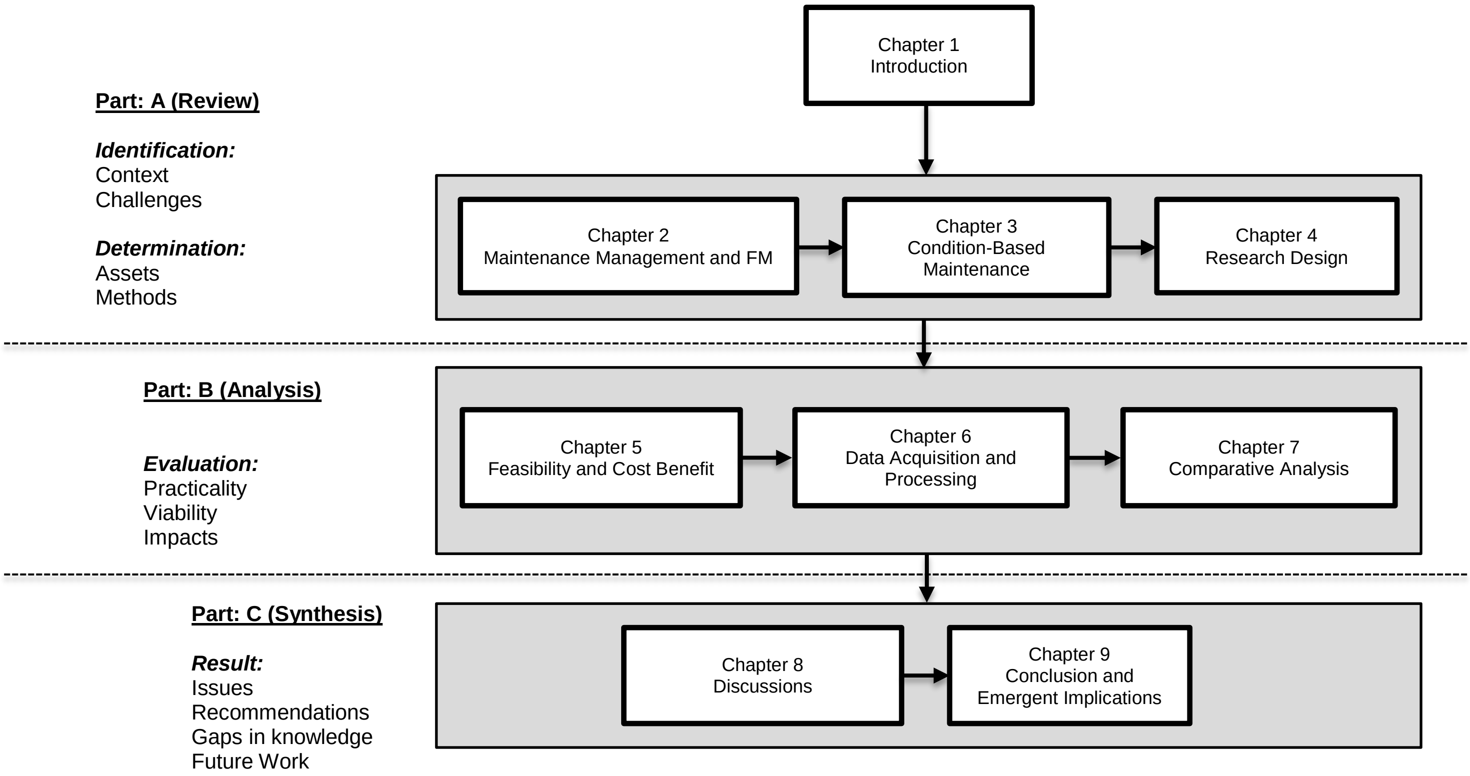
Chapter 4 details the research design framework and outlines the application of the mixed-method approach.

1.5.1 ORGANISATION OF THESIS

1.5.1.1 Structure and Chapter Summary

Part	Chapter	Title and Summary
A: Review	1.	**Introduction:** An introduction to the study discussing the problem area with foundation from research conducted as part of Master of Research (MRes) programme. It also covers the definition of the main aim, objectives and research question. Furthermore, the overall research methodology, demarcation and the structure with chapter summary of the thesis are also outlined.
	2.	**Maintenance Management and FM:** This chapter details the relevant underlying background issues that motivate the main concepts forming the basis of the research. It firstly analyses the impact and transitional role of maintenance management with a focus on its evolution. Secondly, it examines the context, components and key issues related to overall management of maintenance. Finally, the particular domain of this research is discussed to stress the current position of maintenance management in the built environment.
	3.	**Condition-based Maintenance (CBM):** This chapter will provide a detailed review of CBM literature relevant to this study. It will critically discuss CBM advantages, disadvantage, and research conducted using the most prevalent techniques towards achieving fault detection, diagnosis and prognosis. It will also analyse the application areas and availability of research relating to the built environment.
B: Analysis	4.	**Research Design:** This chapter firstly outlines the main areas of interrogation of this research. Secondly, following the examination of numerous approaches for conducting research, an action research approach using a case study based research design is adopted employing a multi-strand mixed method data collection instrumentations (qualitative and quantitative). Thirdly, details are provided of the selected case and assets. Lastly, the data analysis procedures and research quality and validity are discussed.
	5.	**Technical Feasibility and Cost Benefit Analysis:** This chapter presents a comprehensive investigation and analysis into the maintenance cost, savings and opportunities associated firstly with the existing practices and secondly with the proposed CBM solution. It highlights the methods the researcher implemented to establish the current baseline cost and opportunities which are subsequently cross-examined against the technical feasibility costs to determine whether CBM based predictive maintenance implementation can be financial justified on the case study.
	6.	**Data Acquisition and Processing:** This is the second analysis chapter. The purpose of this chapter is to describe the methodologies implemented and present the quantitative sensor data collection results in preparation for the final chapter in this part, which will conduct a comparative analysis of the results from both analysis chapters.
	7.	**Comparative Analysis of Results:** This is the third and final analysis of results chapter, therefore it aims to combine and cross-examine the results of the previous chapters in order to extract answers for the original research sub-questions. Moreover, in-line with the research methodology, this chapter will also describe and incorporate the qualitative ethnographic observations in to the analysis.
C: Synthesis	8.	**Discussions:** This synthesis chapter will implement the data analysis triangulation methodology in order to analyse all relevant observations from the literature review in Part A and the empirical research presented in Part B of this thesis. The observations are succinctly discussed in the context of the defined research domain (buildings maintenance management) and structured with reference to the original research objectives.
	9.	**Conclusions and Emergent Implications:** This last chapter emphasises the most significant facets of this research on CBM in relation to building maintenance management. Alongside the most relevant conclusions, the emergent implications, with research limitations, are described and a body of future works is proposed. Finally, the original contribution to knowledge is outlined and the activities used to disseminate the findings highlighted.

1.5.1.2 Thesis Schematic



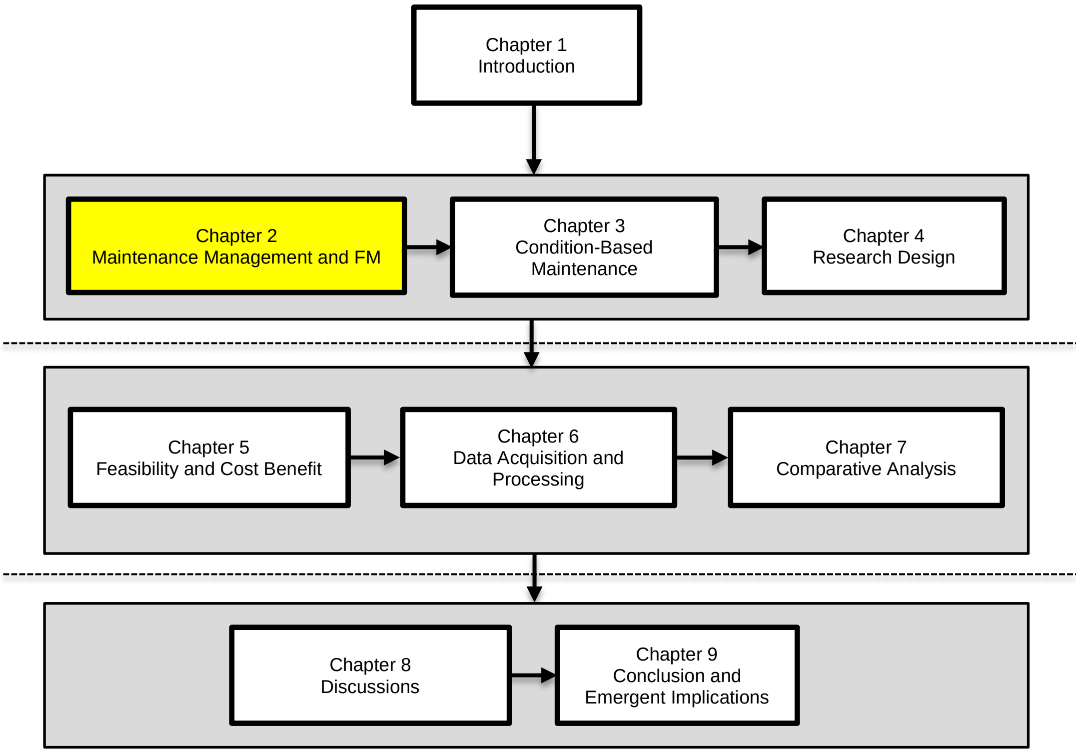
1.6 BOX 1: SUMMARY OF INTRODUCTION

To summarise Chapter 1:

- This thesis details an unprecedented and novel research methodology applied within an industry sector that has been significantly supressed of innovative contributions.
- The research transfers theoretical concepts relating to data, technology and sensors from industries with high value assets and implements those concepts into the domain of building asset maintenance and operations (where assets are often considered to be low or less valuable).
- The main aim of this thesis is to develop the background MRes research by investigating the practicality, viability and impacts of implementing a data driven CBM framework using online vibration analysis in a building maintenance context.
- Furthermore, it sets out to combine condition monitoring and statistical data analysis to enable predictive, informed decision-making in the context of building maintenance management. Moreover, a customised framework will be proposed to demonstrate the viability and practicality of online CBM solution integration for building assets.

The next part of the thesis will provide a thorough analysis of literature relating to the context of the study, i.e. Maintenance Management and FM.

2 CONTEXT TO THE STUDY – MAINTENANCE MANAGEMENT AND FM



This chapter details the relevant underlying background issues that motivate the main concepts forming the basis of the research. It firstly analyses the impact and transitional role of maintenance management with a focus on its evolution. Secondly, it examines the context, components and key issues related to overall management of maintenance. Finally, the particular domain of this research is discussed to stress the current position of maintenance management in the built environment.

2.1 BACKGROUND AND SIGNIFICANCE

In the current digital society of mechanization and automation (Garg & Deshmukh 2006), the reliability of complex systems and associated assets (service or product outputting equipment) is becoming fundamental to everyday life (Kobbacy & Murthy 2008). As a result the philosophy of maintenance (as a way of ensuring reliability), is *'keeping the wheels in our society rolling properly'* (Holmberg et al. 2010, p.1). The potential impact, importance and practical application of maintenance towards the reliability aspects of complex systems can be evidenced in a wide spectrum of territories; from advanced communication systems to modern day transportations, buildings, utility networks and many more as shown in Figure 1.

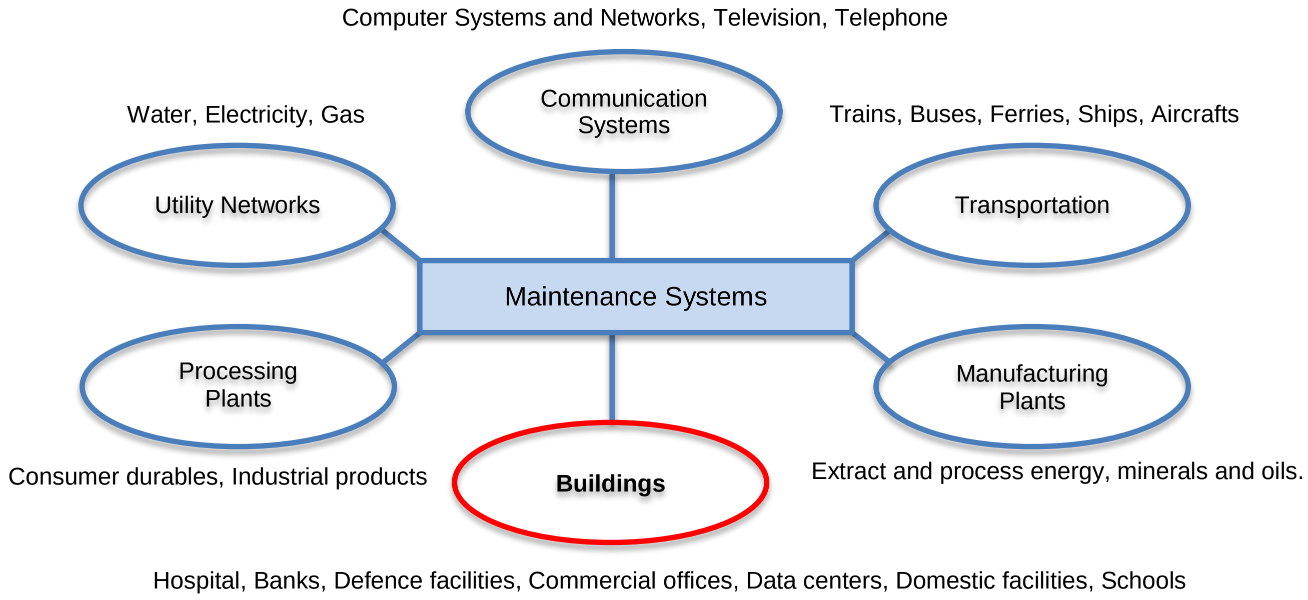


Figure 1: Spectrum of maintenance territories

Source: Adapted from (Kobbacy & Murthy 2008; Holmberg et al. 2010)

Regardless of system, observational and analytical reliability evidence suggests that there is generally an ingrained risk of asset failure caused by age and/or usage deterioration (Wang 2002; Kobbacy & Murthy 2008; Holmberg et al. 2010). Therefore *when,* (in contrast to if), a failure occurs the ramifications can be startling. For example, the failure and/or unavailability of critical networks, buildings and operational facilities can not only cause immense inconvenience to end-users, but also provoke major economic losses, legal and contractual challenges as well as interrupting operational outputs. Furthermore, in certain cases the consequences can include serious injury and potential loss of human life (e.g. aircraft crash during flight, explosion on oilrigs or power/nuclear plants) (Kobbacy & Murthy 2008; Holmberg et al. 2010).

For example in 2014, an AirAsia plane crash killed all hundred and sixty-two people on board. The consequent yearlong investigation report released in December 2015 concludes inadequacies with the maintenance system triggered the occurrences of repetitive unresolved technical faults with the faulty asset (‘Rudder Travel Limiter’). Alarmingly, the report states that the maintenance crews were aware of the fault in question, as it had occurred twenty-three times in the past year (BBC, 2015; Lamb, 2015). This highlights the potential severe consequences of inadequately resolving the detected faults, without diagnosing root cause.

Similarly, in 2010, the British Petroleum (BP) Gulf of Mexico oil well explosion killed eleven people and countless wildlife, halted businesses and tourism, whilst also damaging the reputation of BP. The clean up cost of the incident after five years stands at $28 billion, with an additional $20 billion compensation fund (Telegraph, 2015). The federal report published in 2014 blames *‘bad management’* and *‘operations’* towards inadequate testing of the failed asset (‘blowout preventer’). Although the ownership and maintenance of the asset according to BP is the responsibility of the outsourced operations company, fundamentally, the cause of one of the worst environmental disasters in American history is attributed to inadequate maintenance and notably associated to BP (Guardian, 2014; Telegraph, 2015). Therefore, in addition to economical impacts, the long-term effects of some failures can have significant reputational and environmental consequences.

2.2 HISTORY AND EVOLUTION

Maintenance is not a new idea, however (as demonstrated by Figure 2) the sphere of maintenance management is constantly changing (Kobbacy & Murthy 2008). Consequently, there is an immense amount of literature on maintenance, which spans over fifty years. The underlying facets and the associated key literature are discussed below.

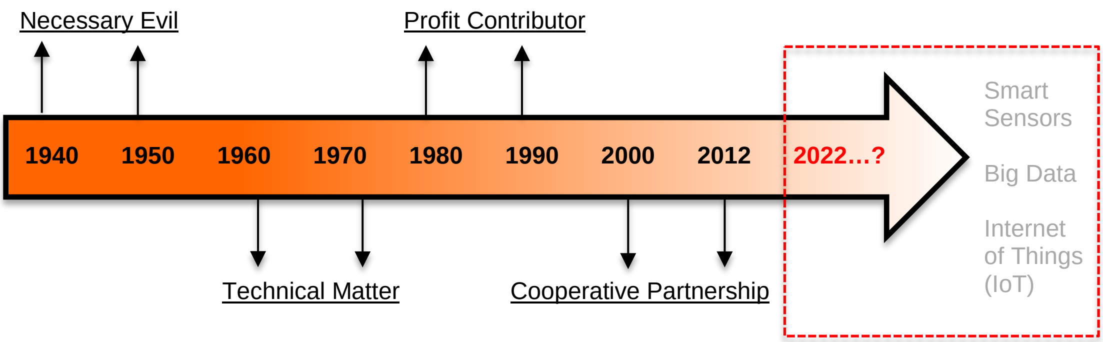


Figure 2: The evolution of maintenance

Source: Adapted from (Kobbacy & Murthy 2008; Holmberg et al. 2010)

1940s and **1950s – Necessary Evil:** Nearly all maintenance actions were corrective (actions applied after a failure has occurred) with a mentality of 'if it isn't broke, don't fix it'. Consequently maintenance was generally considered as a necessary evil with annoying, inevitable and unmanageable costs (Pintelon & Parodi-herz 2008; Kobbacy & Murthy 2008; Ahmad & Kamaruddin 2012; Shin & Jun 2015). However, a small minority of pioneering organisations (i.e. Rio Grande Railway Company and US Army) started to investigate data monitoring with a goal of technically understanding and preventing failures (Martin 1994; Prajapati et al. 2012). Literature focused on mathematically angled reliability research (Pintelon & Parodi-herz 2008).

1960s and **1970s – Technical Matter:** Progressively, companies started to acknowledge that certain failures of mechanical assets were caused by preventable age-based fatigue and/or operational degradation (Pintelon & Parodi-herz 2008). To combat such failures, precautionary or preventive maintenance actions were commonly scheduled by companies with the mentality that cost savings could be achieved in the long term from averting the failures (Al-Najjar 2012; Pintelon & Parodi-herz 2008; Ahmad & Kamaruddin 2012; Kobbacy & Murthy 2008).

However, cost-effectively regulating the frequency of the actions was challenging, especially as the understanding of historic failure patterns and data were limited.
Consequently, maintenance became a 'technical matter' where engineering and statistics were applied to achieve a greater understanding of patterns, thus creating the 'Reliability Engineering' branch of maintenance research (Pintelon & Parodi-herz 2008; Holmberg et al. 2010; Prajapati et al. 2012).

While the main literature focus remained mathematical, the orientation was now based on modelling policy optimisation (i.e. to determine the optimum preventative frequency or interval), however these theoretical models lacked realistic hypotheses and therefore were difficult to apply within industry resulting in an unfortunate gap between academics and practitioners (Prajapati et al. 2012; Pintelon & Parodi-herz 2008; Brown & Sondalini 2013).

Moreover, the influence of optimising technical solutions via statistically considering engineering (maintainability at the design and development stage), science (achieving better understanding of material degradations), and reliability (probability patterns) in parallel with economical, legal and operational applicability instigated perceptions to be progressively shifted and alternative methodologies to be developed (i.e. Predictive or Condition Based) (Prajapati et al. 2012; Martin 1994; Pintelon & Parodi-herz 2008).

Additionally, as reliability knowledge improved in the late 1970s, the effectiveness and the deceptive benefits of exclusively applying preventative actions on all assets (simple and complex) began to be doubted with growing apprehensions of 'over-maintaining' assets unnecessarily (Kobbacy & Murthy 2008; Pintelon & Parodi-herz 2008). This steadily triggered a change in direction and uptake of predictive maintenance actions based on condition monitoring (Pintelon & Parodi-herz 2008; Prajapati et al. 2012). However, completely shifting to predictive maintenance was limited to 'high-risk', technically feasible and economically beneficial applications (such as nuclear power plants and aviation - aided by the introduction of Boeing 747s). Although in the early 1980s, as monitoring equipment became cheaper and accessible, the techniques started to be utilised outside of 'high-risk' domains such as manufacturing (Tinga 2010; Pintelon & Parodi-herz 2008; Ahmad & Kamaruddin 2012).

1980s and **1990s – Profit Contributor:** During this period, parallel with a general increase in the complexity of assets, the competitive marketplace got more demanding (i.e. the cost of maintenance was rising and downtime of assets becoming less tolerable). The expectation to lower costs (maximising investment to achieve highest profitability) was supported by better understanding of failures, enhanced management techniques, and new technologies (Brown & Sondalini 2013; Pintelon & Parodi-herz 2008).

Moreover, the concept and education of maintenance risk along with environmental and safety factors became very important (Brown & Sondalini 2013). Consequently, 'Centres of Excellence' (e.g. DuPont, ICI, Shell, UKAEA) started to emerge focusing on development of life cycle engineering (demonstrating another shift on the history of maintenance). This required analysis of whole life costs (i.e. design, build, maintain, decommission and disposal) with the goal of economic investment justifications and increasing the ARMS (availability, reliability, maintainability and safety) features (Pintelon & Parodi-herz 2008; Brown & Sondalini 2013; Kobbacy & Murthy 2008).

Therefore, in contrast to companies accepting and managing innate maintenance features, they started to create dedicated departments and communicate requirements for consideration much earlier in the design and commission stages (Brown & Sondalini 2013), thus progressively, maintenance functions began to be better appreciated internally (contributor to profit) (Pintelon & Parodi-herz 2008). Furthermore, during the 1990s, 'The Institute of Asset Management' was created in the UK to aid collaborate and promote knowledge, understanding and good practice associated with strategically and cohesively managing assets (Brown & Sondalini 2013).

Literature focus remained on the optimisation and performance aspects, for example one of the notable contributions (according to Garg & Deshmukh (2006)), was presented by Dekker & Scarf (1998) who reviewed 112 papers and discussed application cases within civil engineering, aeroplanes, and power system maintenance in order to provide classifications of maintenance optimisation models (operational and strategic) and highlight that there is a requirement for optimisation in the mentioned areas (Dekker & Scarf 1998).

Moreover, Dekker & Scarf (1998) identified that the limited industry evidence relating to the application of maintenance optimisation may be a temporary problem resulting from a lack of engineer education and problem owners inadequately organising the problems. Additionally, they conclude that *'maintenance optimisation theory is far from complete'* with all the cases discussed (particularly involving maintenance of multi-component assets) demonstrating that *'we are only at the beginning'* (Dekker & Scarf 1998, p.118). However, the industry application cases discussed by Dekker & Scarf (1998) appear to have been analysed through a descriptive and to an extent, a theoretical approach that fails to evidence the practical viability.

On the performance measurement aspect, the comprehensive review by Pintelon & Puyvelde (1997) demonstrates that the numerous systems of measurement (i.e. surveys, indicators, reference numbers) applied in practice are generally ineffective. This is due to the fact that the performance measurement is an enormous (yet signifcant) project which is difficult to introduce correctly for the satisfaction of all stakeholders (different hierachical levels), i.e. perceptions of performance varies depending on stakeholders such as accountants, top management, engineers (Pintelon & Puyvelde 1997). Consequently, they conclude that expectation management is required along with early engagement and agreement of key performance indicators at the appropriate levels.

2000 onwards – Cooperative partnerships: The immense effort directed on the domain of maintenance from multiple disciplines (e.g. engineering, reliability, mathematics etc.) has led to the production of one of the newest and most dynamic management sciences (Kobbacy & Murthy 2008; Holmberg et al. 2010). Furthermore, the combined efforts applied by various research domains, parallel with the effects of numerous drivers and enablers (e.g. technological (r)evolutions, globalization, increasingly complex assets, better investment justification and value for money) appear to have changed the perception of maintenance into a mature component of the business strategy, respected on similar levels as other strategic partnerships (Pintelon & Parodi-herz 2008; Holmberg et al. 2010; Garg & Deshmukh 2006).

Over the last decade evidence is being accumulated that maintenance can impact the future of organisations with its direct connection to profitability and competitive added value (Eti et al. 2006; Chanter & Swallow 2007; Kobbacy & Murthy 2008; Holmberg et al. 2010; Ahmad & Kamaruddin 2012; Al-Najjar 2012; Zhang 2013; Zhu et al. 2015). As a result the field is now considered as an important partner for success and revenue generation rather than an inconvenient necessity.

Furthermore, there appears to be an acceptance in the literature that correctly developing and implementing optimal maintenance strategies can prevent asset failure occurrences, improve system reliability while reducing the costs and improving return on investment (Eti et al. 2006; Gustavsson et al. 2014; Verma & Subramanian 2012; Rajan & Roylance 2000; Al-Najjar 2012). However, it is important to highlight (as emphasised by Garg & Deshmukh 2006; Pintelon & Parodi-herz 2008; Holmberg et al. 2010) that problems relating to maintenance management are very much evident, and far from the deceptive impression that all problems have been resolved (especially alignment with business strategy, industry application and optimisation).

Pintelon & Parodi-herz (2008) stress that since majority of reseach still focuses on the tactical and operational planning aspects, there are concerning gaps between top management level (where the overall maintenance strategy is established) and the tactical level (which leads to operational level, where the maintenance concepts are designed and implemented).

Therefore, Pintelon & Parodi-herz (2008) specifically suggest that there is a need to effectively establish a link that enables alignment of strategic phases with tactical and operational.

Nowadays, it is also notable that maintenance has evolved into a complex function that requires a multidisciplinary management skillset. This may be contributing to the threatening gap since there is a requirement for multi-dimensional skillset alignment (operations, management and technical) that are adaptable to survive with the dynamic environment of the business (Pintelon & Parodi-herz 2008). Therefore, successful and effective industry applications of most appropriate and optimised maintenance strategies that align and harmonise the maintenance philosophies with business strategies to generate a profit, is very much an aspiration rather than a reality (Pintelon & Parodi-herz 2008).

Furthermore, looking into the future, the evolutions and advancements associated with next generation intelligent sensors combined with new analytical abilities of large datasets (big data) and integration possibilities demonstrated by the ‘internet of things’ concepts, can only continue the exciting evolution of this young management science. Moreover, in parallel with technology advancements, this research is based on the belief that there will also be a natural shift in the demands and skillsets of maintenance managers and engineers towards the adoption of technology, data and acquisition of technical insights using modern maintenance tools.

Consequently, a lack of appropriate innovative tools, techniques and continuous improvement towards the adoption of the current engineering concepts may hinder the reputation of the maintenance industry, which undoubtedly will need to demonstrate the application of technology in order to be attractive to the technology savvy generation.

The above vision of the future not only forms part of the motivation for conducting this study, but is also reinforced by maintenance technology research presented by authors such as Holmberg et al. (2010) who discuss concepts of ‘e-maintenance’ and the theoretical potential associated with the evolution/revolution of various technologies techniques.

2.2.1 Multidisciplinary Domain

Consequent of its evolution, maintenance nowadays is a dynamic and complex management science that covers multiple disciplines as shown in Table 1.

Engineering	Performance and degradation of an asset is dependent on design and production of the asset - i.e. In contrast to poor designed assets, well-designed assets are more reliable (less prone to failure). Therefore, maintainability is considered during design and development via life cycle mindsets.
Science	Selecting the incorrect material can have a serious long-term consequence and impact on the subsequent maintenance actions needed. As a result, it is vital to identify and understand the physical mechanisms that are at play and their influence on the degradation and failure.
Economic	The cost of maintenance can be one of the most significant components of the total operating budget for a business depending on the industry sector. The two types of costs (annual cost and cost over the whole life cycle of the asset) can be further broken down into Direct (*labour, material etc.)* and Indirect (*consequence of failure*).
Legal	All companies must adhere to and operate assets within the boundaries of relevant legislations (e.g. contractual, statutory and/or mandatory). This is important in the context of maintenance out-sourcing and maintenance of leased equipment. In both cases, the central issue is the contract between the parties involved, which importantly will drive dispute resolution (i.e. when there is a disagreement between the parties in terms of the violation of some terms of the contract).
Statistics	Degradation and failures occur in an uncertain manner. Therefore, the analysis of such data requires the use of statistical techniques. Statistics provide the capability (via concepts and tools) to extract information from data thus enable informed decisions making.
Operational Research	Operation research provides the tools and techniques for theory testing, model building, analysis and optimization. Often, theoretical and analytical approaches fail in practice and one needs to use simulation approach to evaluate the outcomes of different decisions in operational environment and to choose the optimal (or near optimal) strategies based on empirical evidence.
Reliability theory	Reliability theory considers the interdisciplinary use of probability, statistics and stochastic modelling, combined with engineering insights into the design and the scientific understanding of the failure mechanisms. Therefore, the research encompasses numerous features of reliability including: management, engineering, science, technology, modelling, analysis and optimisation.
IT and Computer Science	The advancements in this discipline is providing opportunities for maintenance optimisation using technology focused tools and techniques to drive actions. Furthermore, nowadays, the operation and maintenance of assets generates large quantities of data. Consequently, there is a need for efficient ways to store and manipulate the data and to extract meaningful information. In addition to the hardware such as intelligent sensors, computer science provides a range of artificial intelligence techniques (e.g. data mining, expert systems, neural networks), which are very important in the context of maintenance research and application.

Table 1: The disciplines involved in maintenance

Source: (Kobbacy & Murthy 2008)

2.3 THE COMPLEX MANAGEMENT CONTEXT

Analysing the numerous definitions of maintenance in the literature, the majority consensus appears to emphasise that it as a *'set of activities'*, which are usually a combination of technical and/or administrative (BS 3811, 1993; Dhillon, 2002; Pintelon and Parodi-Herz 2008; RICS, 2009; Tinga, 2010; Ahmad and Kamaruddin, 2012; Shin et al. 2015).

However, as stressed by some scholars (Pintelon and Parodi-Herz, 2008; Tinga, 2010; Shin & Jun, 2015), such definitions have tendencies to incorrectly disguise the true complex, dynamic and influential nature of maintenance in practice as nothing but a simple endeavour. Figure 3 demonstrates the potential elements involved in the complex context of maintenance.

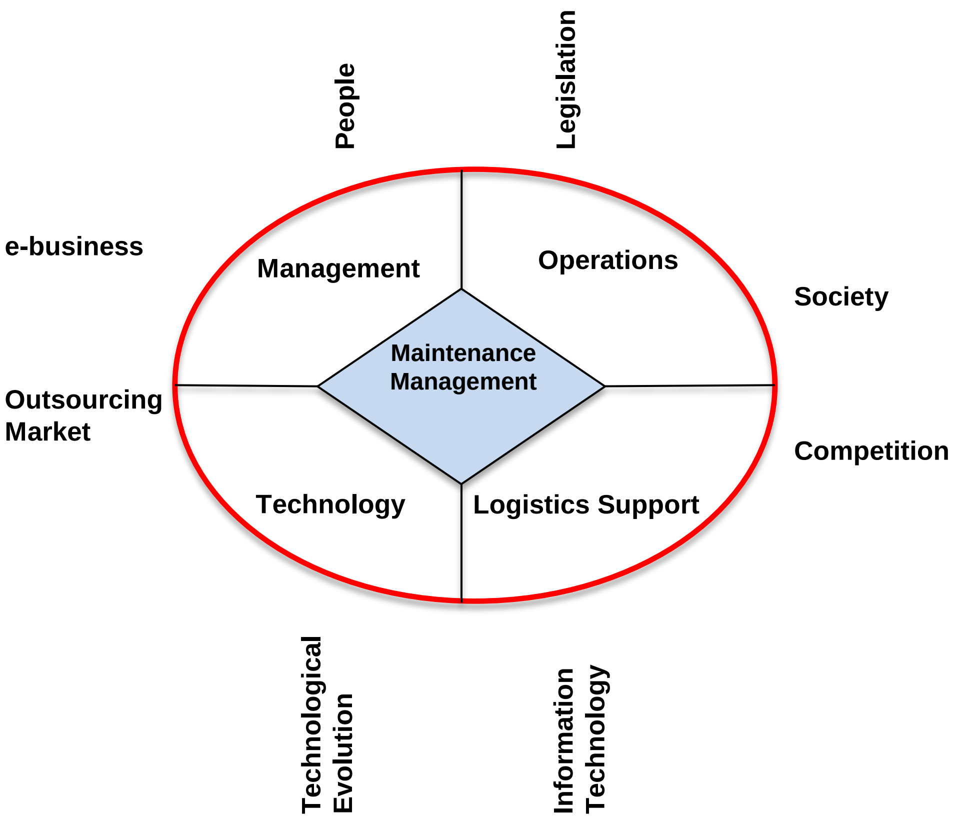


Figure 3: Complex context of maintenance

Source: Adapted from Pintelon and Parodi-Herz (2008)

Nowadays, the dynamic role of the maintenance manager requires harmonising technologies, operations and logistic support components with the core business outputs. Additionally, balancing these elements in an economical manner requires consideration of numerous outside influencers such as people, legislations, society, outsourcing market, competition, IT and technological evolutions (Garg and Deshmukh, 2006; Pintelon and Parodi-Herz 2008; Kobbacy & Murthy, 2008). Furthermore, since the function is rooted within the core of an organization and affected from numerous internal components, the balancing act requires strategic considerations such as:

- **Management** – covers key decisions (e.g. *'what'* and *'how'*).
- **Technology** – the tools available and/or required to support maintenance actions.
- **Operations** – ensuring core business activity is aligned to maintenance services and labour.
- **Logistics Support** – covers the planning, organising and delivering the maintenance and necessary resources (e.g. inventory, spares etc.).

Therefore, the overall management function is key to not only enabling effective application of maintenance, but also ensuring all the relevant considerations such as the business environments, objectives and commercial scopes, are aligned with the maintenance decision-making. As a result, the practise of maintenance management (or in other words collectively managing the individual technical and administrative elements relating to maintenance) becomes overwhelming and intricate when analysed in the practical environment (Pintelon and Parodi-Herz 2008).

To emphasise such intricacies, this section will analyse the most significant elements that support and influence the goal of maintenance management, which includes stakeholders, technical and commercial aspects, notable issues and the cost of maintenance.

2.3.1 MAINTENANCE MANAGEMENT

In practice, the process of successfully and efficiently managing maintenance activities requires maintenance management, which can be defined as:

> *"All activities of the management that determine the maintenance objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics" (*British Standards Institution, 2010).

The definition highlights several challenging activities including establishing strategies, responsibilities and the actual implementation through planning, control and improvement. Nevertheless, according to Pintelon & Parodi-Herz (2008), pragmatically, the core vision of maintenance management is the control and optimisation of total asset life cycle. In other words, it's a process that not only aims to economically maximise the overall availability and reliability objectives during operations, but also ensure the assets maintainability and safety aspects are under considerations throughout all life phases (e.g. design, development, install, operations and disposal).

Similarly, CIBSE Guide M (CIBSE 2008) stresses that maintenance management can involve a 'technical' element in addition to the control of activities. The technical management component requires establishing the 'what', 'how' and the 'when' (CIBSE 2008). Consequently this not only includes detection and diagnosis of faults (i.e. the 'what'), but also the monitoring and analysis of technical information and condition indicators (the 'how'); which are combined with instructing protocols and probability (or experience based assumptions) to enable preparation and contingency planning (the 'when') prior to the situation occurring (e.g. loss of functionality due to a failure) (CIBSE 2008; RICS 2009).

Furthermore, Guide M (Cibse 2008) highlights that the control of the technical element endeavours to balance the necessary service inline with a business strategy driven management focus on minimum financial expense, operations (e.g. management of labour, identification and prioritisation of coordinated actions) and logistic support (e.g. availability, planning and organising of spares and equipment). The core outcome generally includes decision-making based on establishing of budgets, continuous expenditure monitoring and prioritisation of maintenance activities (CIBSE 2008; RICS 2009).

Therefore, to achieve the vision and objectives of maintenance management, management is necessary on three different levels, which encompasses strategically establishing the maintenance strategy, tactically planning and scheduling the maintenance activities and finally operationally executing those activities (Kobbacy & Murthy 2008; Milje 2011; RICS 2009; CIBSE 2008). Figure 4 demonstrates this further by highlighting the core components necessary at each level.

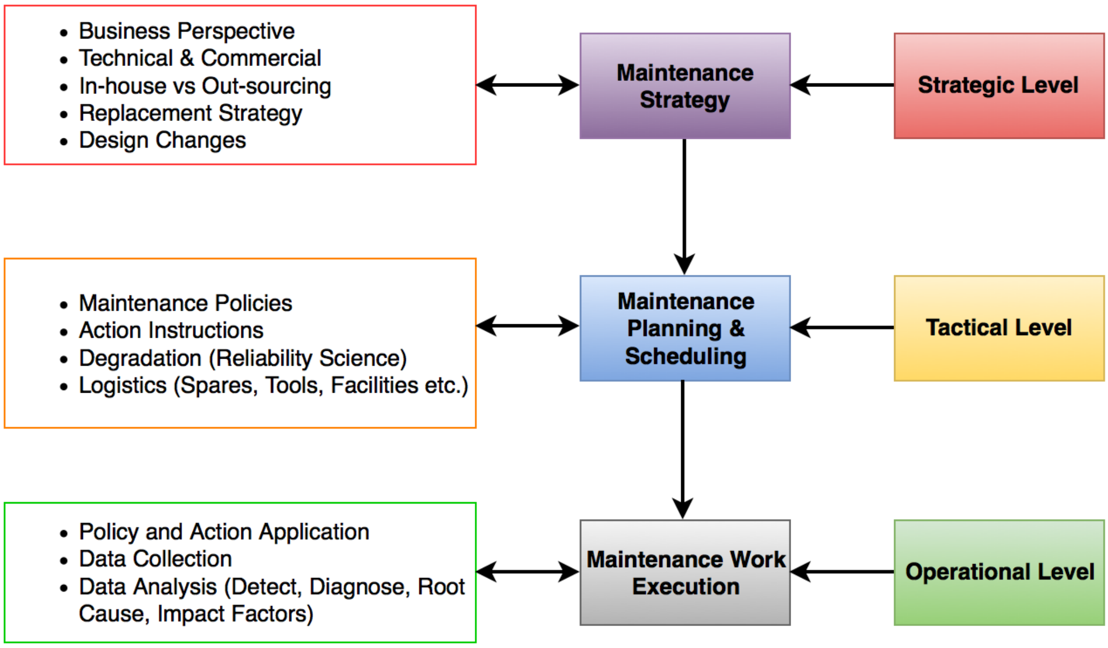


Figure 4: The management of maintenance

Source: Adapted from (Kobbacy & Murthy 2008)

Maintenance Strategy: Aligned with the business strategy, this aims to incorporate the business perceptions with overall technical and commercial considerations in order to complement decision-making on key concepts such as replacement policies or undertaking maintenance in-house vs. outsourcing.

Planning and Scheduling: The maintenance strategy is core to the tactical application of maintenance planning and preparation. The main actions undertaken at this level involves establishing maintenance policies through understanding degradation (e.g. based on historic failure data, manufactures recommendations and/or appropriate industry standards). Additionally, a logistical support network is determined to enable access to spares and inventory.

Execution: The tactical planning and scheduling will drive the operational execution of the maintenance work on assets, e.g. based on the selected maintenance policy and schedule, appropriate resources are directed to undertake the established maintenance instructions, collection and analysis of data to fulfil overall maintenance strategy.

On balance, it is clear that the effective management of maintenance activities appear convoluted by a variety of internal and external influences. Nevertheless, by analysing the core components at the three mentioned levels it is possible to focus specifically on key elements that directly affect the overall business objectives and relevant stakeholders.

2.3.2 STAKEHOLDERS

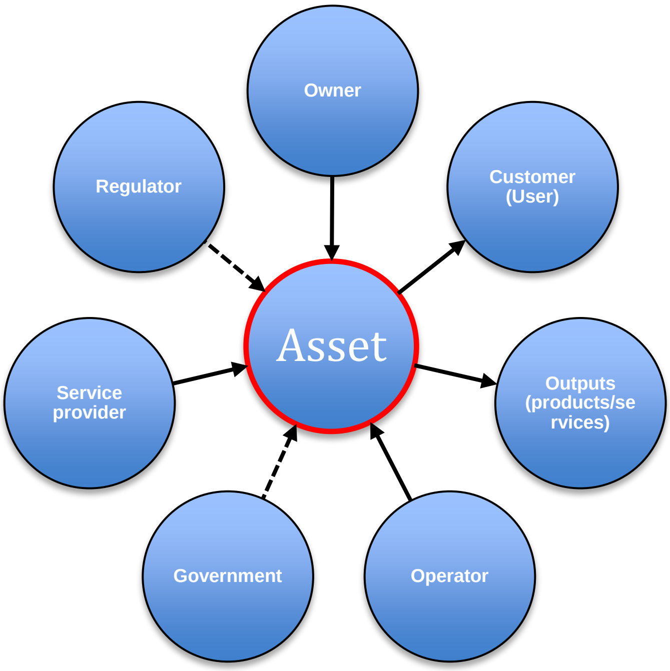


Figure 5: Stakeholders involved in maintenance of an asset
Source: Adapted from (Kobbacy & Murthy 2008)

Figure 5 highlights the intricate stakeholder involvement when considering the maintenance of a particular asset in the context of this study. Moreover it reveals support for the complexities associated with both the context and management of successful maintenance implementation. However, the specific number of stakeholders involved will naturally depend on the environment, contractual arrangement and asset under consideration.

As an example, the owner of the assets may be different or same as the operator and/or the service provider. Furthermore, customer/user of the asset will be anticipating the outputs (products/services), therefore any interruptions through downtime to maintain or failure can affect the services and outputs to customers. Meanwhile, the technical and administrative maintenance activities all require compliance within regulators and government legislations to ensure adequate risk management and health and safety fulfillment.

Nevertheless, the most common underlying association between the stakeholders and maintenance management appears to be technical and/or commercial motivations derived from overall business goals and addressed in the maintenance strategy (Kobbacy & Murthy 2008; Holmberg et al. 2010).

2.3.3 TECHNICAL AND COMMERCIAL COMPONENTS

Figure 6 shows the key technical and commercial components that require consideration as part of the maintenance strategy:

- Maintenance actions (e.g. preventive, reactive, predictive), the degradation of asset and its production rate are the key asset specific considerations. These link the technical and commercial components with the business goals.
- The key technical elements relate to the assets functional requirements, design and fundamentally the maintainability requirements, which determine the maintenance techniques.
- Logically the key commercial aspects focus primarily on financial added value in-line with the business goals.

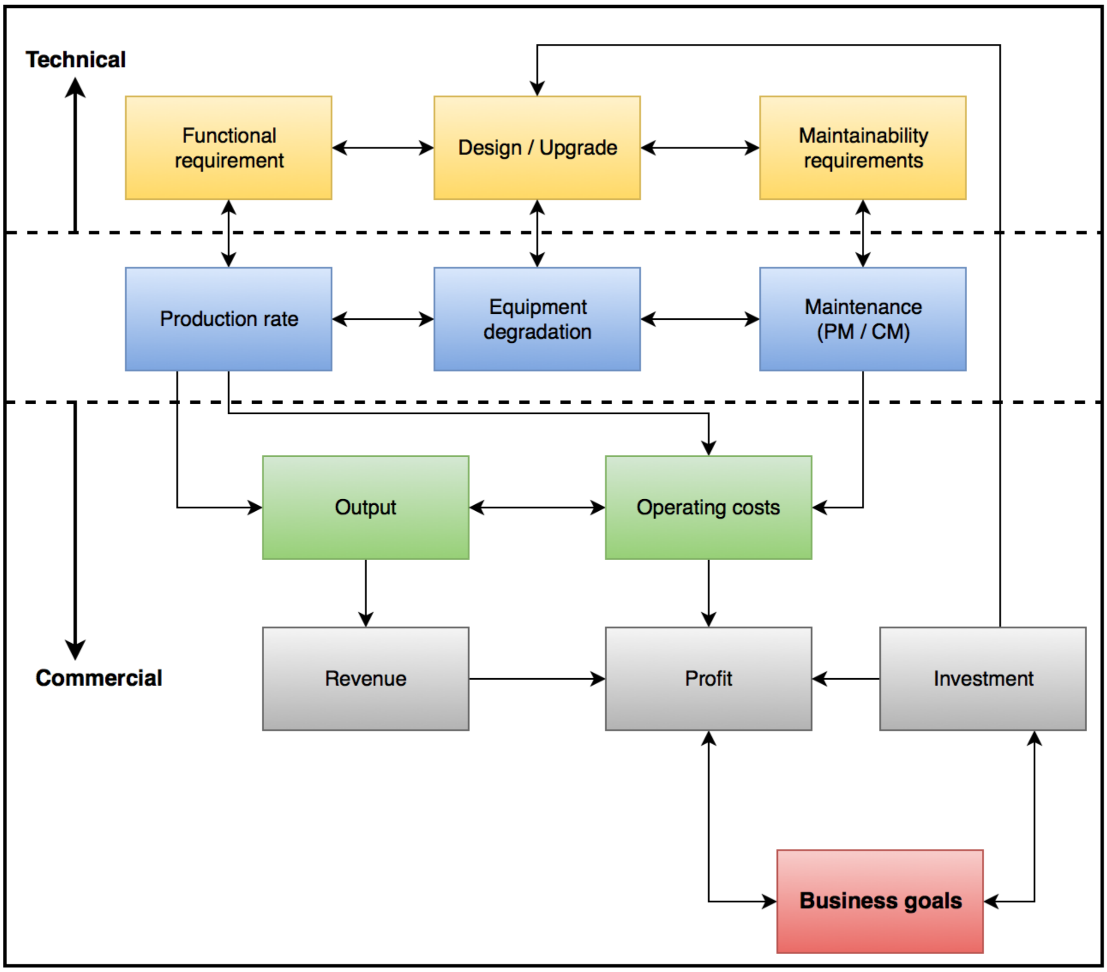


Figure 6: Key technical and commercial components

Source: Adapted from (Kobbacy & Murthy 2008)

2.3.4 KEY ISSUES IN MAINTENANCE

Figure 7 shows a top-level view of the variety and complexity of issues relating to maintenance.

The interconnected issues appear to epicenter around the 'Concepts/Techniques' of maintenance, thus indicating the significance and impact of the techniques implemented. Moreover, whilst one of the fundamental driver of the business objectives is usually optimisation of maintenance actions and concepts, achieving optimisation itself can be an issue (Kobbacy & Murthy 2008; Holmberg et al. 2010). Additionally, the business objectives generally facilitate asset acquisition (influenced by asset design), operations (impacts the asset state), technologies (impacts the data collection) and computer packages, which impact not only the data collection, but also the analysis and modelling elements of maintenance.

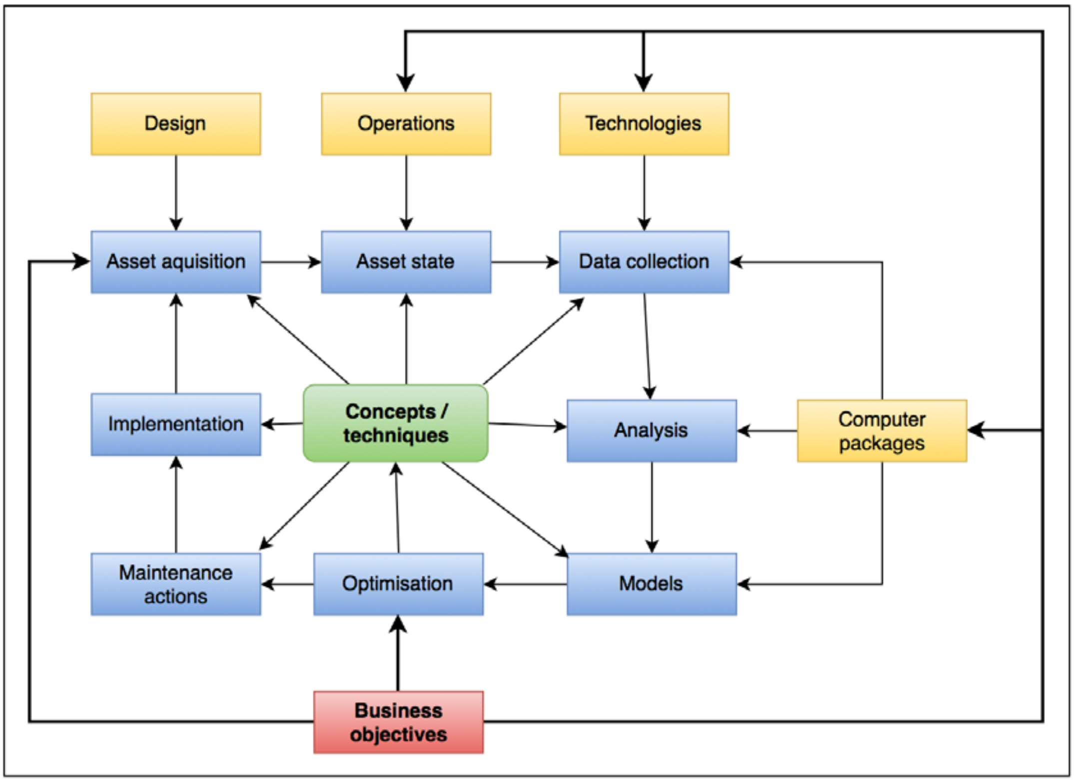


Figure 7: Key issues relating to maintenance
Source: Adapted from (Kobbacy & Murthy 2008)

2.3.5 COST OF MAINTENANCE

The extensively discussed topic of maintenance cost, and the establishing of its significant impact on productivity and profit, can be traced throughout the history and evolution of maintenance management (as discussed in section 2.2). However, quantification of the precise costs and associated savings continue to be debated.

For example, Mckone & Weiss (1998) state that company-wide expenditure on maintenance can roughly equal its net income, while Ahlmann (1998) estimates that direct costs represent around half the total maintenance costs (focused within Swedish industry). Similarly, Mobley (2002) suggests that the cost of maintenance in some industries (i.e. manufacturing - iron and steel, pulp and paper) can be around 60 per cent of the cost of production, whilst in others (i.e. food-related industries) it can be around 15 per cent.

However, in contrast to Mobley (2002), Tsang (2002) states that the maintenance expenditure within the UK manufacturing industry can be between 12 and 23 per cent of the total operating cost. Yet, according to Garg & Deshmukh, on par with energy costs, maintenance expenditures are one of the largest segments of any operational budget, for example in refineries 30 per cent of total workforce form the maintenance and operations department (Garg & Deshmukh 2006).

Similarly, Eti et al. (2006) state that the cost can be as much as 40 per cent of operational budget within ‘large-scale plant-based industries’. Furthermore, they highlight that a company could be experiencing financial difficulties should the annual cost of maintenance exceed 5 per cent of the asset value.

In the midst of all these percentages, it can be prudent to deduce that the cost of maintenance is a major expenditure component to any organization. However, focusing on overall cost percentages alone can be deceiving, since the ‘maintenance cost’ is not as important as the ‘maintenance budget’ since the budget will govern the maintenance actions (Gupta et al. 2014). Additionally, the effectiveness of maintenance contributes to the cost; therefore improving the effectiveness creates an opportunity for significant financial savings (Mobley 2002; Eti et al. 2006; Gupta et al. 2014).

Mobley (2002) highlights a significant gap between the ‘productivity and profit’ of maintenance management effectiveness in American because although more than $200 billion is annually spent on maintenance of plant and facilities, a third of every dollar is wasted due to ‘unnecessary maintenance’ or maintenance undertaken ‘improperly’.

The effectiveness of maintenance is difficult to quantify or appreciate since a lack of maintenance is generally perceived as the cause of breakdowns, yet when breakdowns do not occur it is challenging to evidence that effective maintenance prevented the breakdown or reduced risk relating to it (Mobley 2002; Al-Najjar & Alsyouf 2004; Gupta et al. 2014).

Al-Najjar and Alsyouf (Al-Najjar & Alsyouf 2004) emphasise that by using the most efficient maintenance approach, asset failure can be minimised to zero. As a result implementing an efficient maintenance policy can increase an organizations production capacity while reducing maintenance costs. They conducted a comprehensive literature survey and concluded that academic studies did not detail a methodology to calculate and/or estimate actual cost, profit or saving components of maintenance. Furthermore, they suggest that this is consequent of maintenance impacting on a variety of complex areas, therefore it is difficult to estimate indirect maintenance costs such as loss of income due to breakdowns, poor quality, loss of customers, unavailable facility, reputation damage.

Moreover, they state that direct maintenance costs are split into two areas, firstly the internal costs (such as direct labour, materials (spare parts), and overheads (e.g. training, administration, tools and other expenses)), and secondly external costs such as outsourcing from specialist equipment manufacturers. These direct costs of maintenance are usually quantifiable. In contrast, indirect costs refer to all incidentally related maintenance costs and are more challenging to estimate and quantify (Al-Najjar & Alsyouf 2004).

Indirect costs are ascribable to maintenance factors, which result in impacting production, loss of customers, reputational damage and market shares. Fundamentally these costs allude to situations where maintenance deficiencies have caused the asset to impact negatively on the function it serves, which as a result is affecting the wider organizational function and image (Al-Najjar & Alsyouf 2004).

Similar to Al-Najjar & Alsyouf (2004), Gupta et al. (2014) conducted a comprehensive literature review to conclude that there were countless number of models dealing with maintenance cost and replacement decisions. Having analysed the existing models, they put forward a methodology to evaluate the annual maintenance budget in respect to the asset replacement values. However, similar to majority of methodologies, the method they put forward only considers direct maintenance costs and does not disucsss any of the indirect cost estimations.

Regardless of whether these are direct or indirect, costs associated with long-term assets should be evaluated in the context of Life Cycle Cost (LCC) which is *'the total cost of ownership of an item, taking into account all the costs of acquisition, personnel training, operation, maintenance, modification and disposal'* (Al-Najjar & Alsyouf 2004, p.644).

This also supports and is necessary in the objective of maintenance management, controlling and optimising total asset life cycle (Pintelon & Parodi-Herz, 2008). In contrast to Gupta et al. (2014), Al-Najjar & Alsyouf (2004) propose a methodology to estimate both direct and indirect costs, savings and profits that utilises the LCC concept at its core. Moreover, they discussed and outlined fifteen indirect costs which require consideration, as shown in Table 2.

1	Unavailability cost due to failure and UPBFR*.
2	Performance inefficiency costs due to idling, minor stoppages (short stoppages) and reduced speed.
3	Poor quality costs due to maintenance deficiency.
4	Idle fixed cost resources such as idle machines and idle worker costs during breakdowns.
5	Delivery delay penalty costs due to unplanned downtime.
6	Warranty claims from dissatisfied customers due to maintenance-related poor quality, e.g. compensation for product liabilities and repair.
7	Customer dissatisfaction costs due to maintenance-related poor quality, delivery delay or other reasons.
8	Extra energy cost due to disproportional energy consumption.
9	Accelerated wear due to lack of or inefficient maintenance.
10	Excessive, spare parts, buffer and work-in-progress (WIP) inventory costs to avoid the effect of unplanned stoppages on fulfilling delivery schedules.
11	Unnecessary equipment redundancy costs to avoid waiting time after equipment failure or due to UPBFR.
12	Extra investments needed to preserve WIP and redundancies in good conditions.
13	Extra costs due to the absence of professional labour as a result of maintenance-based accidents such as compensation labour costs and costs of using less skilled labour.
14	Penalties for environmental pollution caused by poor equipment condition and accidents related to inefficient maintenance.
15	Extra insurance premiums due to the increased number of accidents related to inefficient maintenance and their consequences.
***Unplanned-but-before-failure replacement (UPBFR):** planned halt of asset to undertake maintenance consequent of detecting imminent failure.	

Table 2: Indirect maintenance costs
Source: Al-Najjar & Alsyouf (2004)

On balance, there appears to be a gap in the literature relating to the cost of service elements of maintenance practices. Moreover, whilst various broad percentages are debated in the literature, there seems to be a lack of detail in relation to the costs, savings and opportunities associated with maintenance strategies (e.g. actions, policies and concepts). For example, although it may be challenging to analyse all necessary elements (i.e. direct, indirect and life cycle costs), literature fails to address the impacts and potential cost, savings and opportunities that can be expected / associated with implementing a particular type of maintenance strategy.

2.4 ACTIONS, POLICIES AND CONCEPTS

Kobbacy & Murthy (2008) suggest that as a young and dynamic management science, the maintenance domain contains a lot of terminology confusions; therefore through surveying and organising extensive maintenance management literature, they propose the use of the following terminology: actions, policies and concepts. Although these terminologies are discussed by numerous authors under various vocabularies (e.g. Wang, 2002; Jardine, et al. 2006; Tinga, 2010; Ahmad and Kamaruddin, 2012), the approach illustrated in Figure 8 appears robust, easy to holistically visualise and comprehensive in the context of this study.

Therefore, as shown in Figure 8, generally, there are two categories of maintenance actions (corrective and precautionary). These actions refer to the basic tasks that are undertaken by an engineer or technician, and can be part of a policy (rule or set of rules) that describes the mechanism for the actions. The combination of different actions and policies in a decision structure that aligns strategic, tactical and operational elements forms maintenance concepts (Kobbacy & Murthy 2008). However, the main focus of research appears to be on the actions and policies (operational and tactical planning aspects), thus a gap exists between overall maintenance strategy (concepts) and business strategy (Pintelon & Parodi-herz 2008).

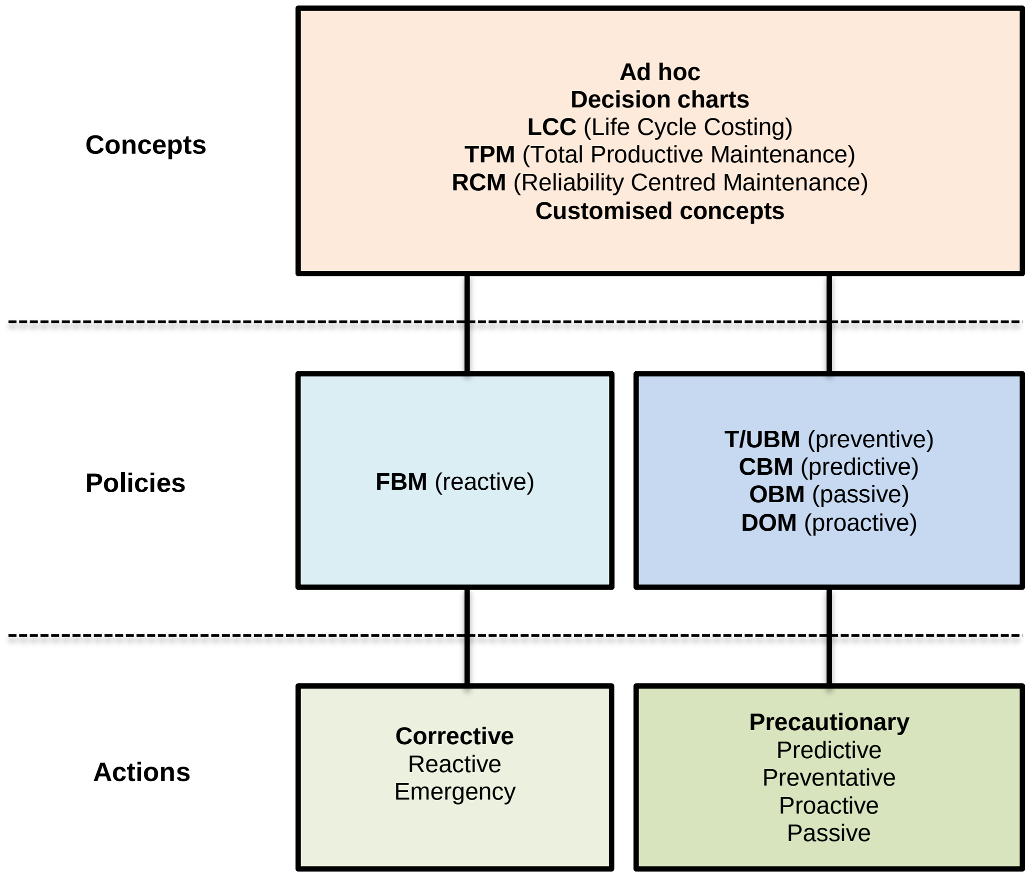


Figure 8: Actions, policies and concepts in maintenance

Source: Adapted from (Kobbacy & Murthy 2008)

2.4.1 MAINTENANCE ACTIONS

2.4.1.1 Corrective Maintenance

CM is in practice the most commonly used strategy, and is also often referred to as reactive, run-to-failure or breakdown. It is applied at the time when the asset requires restoration (to be repaired or replaced) (Blanchard et al., 1995). Despite its frequent use within the industry, this maintenance technique however results in high levels of machine downtime which following causes production loss and significant costs relating to sudden failure (Ahmad and Kamaruddin, 2012).

Depending on the severity of the fault and the environment the asset operates in, two different actions can be applied. Reactive is implemented when the asset requires a quick intervention to restore its original condition, e.g. burst pipeline, a failed light bulb. Emergency maintenance on the other hand is put in place when fault of the asset might be causing a threat to health and safety or poses a risk to the major operations side of the business (Veldman, et al., 2011a; Veldman, et al., 2011b).

2.4.1.2 Precautionary Maintenance (PM)

PM actions are relatively more complex than CM and, as stated by Kobbacy & Murthy (2008), comprehensively detailing each one would require a dedicated and extensive book to be written. However, the fundamental objective of PM actions is to reduce the risk relating to asset failures through anticipating and/or avoiding the failures and the resulting consequences such as the cost associated (Kobbacy & Murthy 2008; Ahmad & Kamaruddin 2012).

Therefore, all PM actions tackle the problem of equipment failure prior to its failure occurrence, although the core principles of the actions may be different (e.g. predictive using vibration analysis technologies, while preventive can involve undertaking routine inspection rounds). Using proactive principles, the underlying aim is to reduce the failure rate or its frequency, at the same time allowing for better product quality and reduction of failure costs (Ahmad and Kamaruddin, 2012).

2.4.2 MAINTENANCE POLICIES

Table 3 summarises the generic maintenance types discussed in the literature, and consolidated by Kobbacy & Murthy (2008).

Policy / type	Overview
FBM (failure-based maintenance) CM: Reactive	CM is undertaken only after a breakdown (i.e. reactively). This policy may be a good option where there is a constant yet random failure rate and/or costs of the breakdowns are low. Also, applied if frequent PM is expensive or impractical to undertake.
T/UBM (time/used-based maintenance) PM: Preventive	Using this policy PM is undertaken after a designated amount of time (e.g. scheduled monthly, annually, or based on hours of operations). PM is believed to be more cost effective than CM. However, corrective maintenance actions are applied when required. Usage based policy assumes that the failure behaviour is predictable and the failure rate is increases with use (i.e. wear out over time). However, in contrast to CBM, this policy does not reduce the probability of failure.
CBM (condition-based maintenance) PM: Predictive	Through this policy, actions are applied each time the value of a set system parameter exceeds a predetermined value (i.e. the condition changes). Similar to T/UBM, it is assumed that CBM will be cheaper than CM. Primitive types of CBM include traditional plant inspection walk-rounds with checklists. However, the popularity of more complex CBM is increasing consequent of the fact that the fundamental techniques such as vibration analysis and oil analysis are becoming more widely available and at better prices. Also, the prospect of better inventory control and management of reduced spare parts holdings is a driver. Although technical feasibility remains the main obstacle, this policy is starting to be explored in wider industries such as manufacturing, and processing, thus is no longer isolated to industries with high value assets (i.e. aviation, aerospace).
OBM (opportunity-based maintenance) PM: Passive	Certain assets and/or its components can only be maintained when the opportunity arises during the maintenance of other more critical components, for example the maintenance of offshore windmills or weapons systems. However, CM is still applied where necessary. The decision of using OBM applicability requires analysis and understanding of asset life, usage and cost considerations. It is generally applied to assets with relatively long lifetime and considered non-critical.
DOM (design-out maintenance) PM: Proactive	DOM focuses on the ergonomic and technical reliability aspects of improving the asset design (earlier stage of product life). Therefore the core goal is to improve availability and safety by make maintenance simpler or even eliminate the requirement to maintain the asset throughout its operational life, which can be pragmatically unrealistic.

Table 3: Maintenance policies

Source: Adapted from (Kobbacy & Murthy 2008)

2.4.2.1 TBM: Planned Preventative Maintenance (PPM)

The most talked about preventive policy of TBM is Planned Preventative (PPM) (also known as periodic-based or scheduled) (Yam, et al. 2001; Ahamad and Kamaruddin, 2012). It involves the evaluation of aging using hypothesis that failure behaviour of assets is predictable based on the bathtub curves, as shown in Figure 9 (Ahamad and Kamaruddin, 2012).

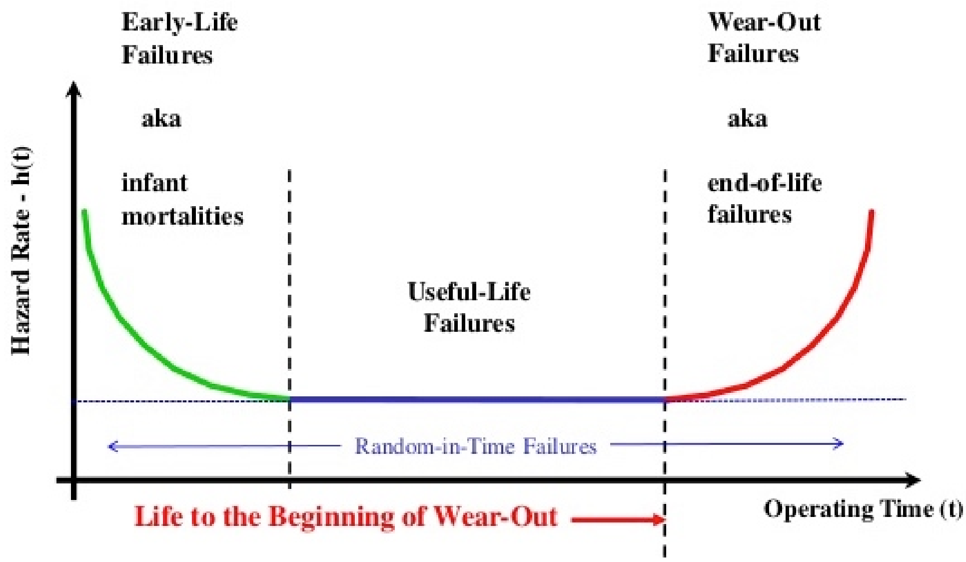


Figure 9: Bathtub curve

Source: Adapted from Ahamad and Kamaruddin, (2012)

In accordance to this belief, it is assumed that the failure rate of assets decreases during the burn-in phase, remains stable during the useful life phase and later increases at the wear-out phase (Ebeling, 1997). Thus failure time data is analysed using statistical reliability modelling (e.g. Weibull distribution model, which is particularly popular as it can model numerous aging classes) to determine the maintenance requirement (Tinga, 2010; Ahmad and Kamaruddin, 2012).

Using such technique, maintenance is not be undertaken on assets until the modelling output identifies that the optimal preventative maintenance requirement is present, or in other words, the asset has reached the wear-out phase because the failure rate distribution is increasing. Subsequently, decisions are made regarding optimal available options (e.g. repair/replace) by considering not only system reliability/availability and safety performance but also lowest possible cost (Tinga, 2010; Ahmad and Kamaruddin, 2012).

Literature indicates that PPM actions can be applied through either experience, which is a conventional practice, or recommendations made by the original equipment manufacturer (OEM), which in contrast is performed on a regular prescribed basis (Nakagawa, 1984; Sheu et al., 1995). The former practice strongly relies on the technicians' and engineers' knowledge and lessons learnt acquired in the past. Based on their experience they can evaluate and predict the condition of a machine. Consequently avoiding the machine failure through applying appropriate PPM actions. The disadvantage of this PPM technique is considerable dependency on the human factor, i.e. the engineers or technicians who are responsible for maintenance can at any point leave the company taking away their valuable expertise on the assets, consequently increasing the operational risk (Ahmad and Kamaruddin, 2012).

The PPM practice based on OEM recommendation is carried out on a pre-agreed set times (for example month, three months and annual). Nevertheless this technique fails to minimise operation costs and maximise machine performance. According to Labib (2004) and later supported by Tam et al. (2006) the OEM is considered to be flawed in this sense due to the fact that firstly each machine operates in a different environment hence requires different PPM schedules; secondly the machines designers focus more on the product delivery rather than later machine failure, consequently they are not as knowledgeable as the engineers or technicians who on regular basis maintain these appliances; lastly the OEM companies at times can act upon hidden agendas recommending spare parts replacements through frequent PMs. An alternative to OEM reference is SFG20 (standard maintenance specification for building services), which is a monthly reviewed library consisting of over 400 maintenance specifications, thus considered the industry standard tool for PM (SFG20, 2014).

2.4.3 MAINTENANCE CONCEPTS

Table 4 summarises the maintenance concepts collated by Kobbacy & Murthy (2008) from various sources of literature.

Concept	Description	Main strengths	Main weaknesses	Generation
Ad hoc	Applying FBM and UBM policies but rarely CBM, DOM and OBM.	Simple.	Decisions are ad hoc.	First
Decision chart	Use of decision charts to help decide on what the right maintenance policy is.	Consistent and allows prioritisation.	Questions and answers are rough.	First – Second
LCC	The maintenance logistics are planned based on detailed cost breakdowns and over the lifetime of the asset. Ideas based on Blanchard et al. (1995) iceberg philosophy of holistically considering seen and unseen costs, not just top of iceberg.	Sound basic philosophy. Maintenance and inventory costs are considered i.e. at design/purchasing stage via costing analysis and engineering design principles.	Resource and data intensive.	Second
TPM	This approach is focused on maintenance and production. It comes from a variety of non-Japanese management practices adapted to fit their culture. It has been successful in the manufacturing industry.	Considers human/technical aspects, and fits into continuous improvement approach. Extensive toolbox available with techniques such as 6sigma.	Time consuming implementation and only relevant in specific industries.	
RCM	Structured approach concentrated on reliability with consideration to system functionality, safety and environment more importantly than cost. It originated from 1960s in high tech/high risk environment (aviation, military).	Powerful approach that has step-by-step procedures.	Resource intensive and difficult to justify and/or apply in low risk and investment positions.	
RCM-based	Approaches focused on remediating some of the perceived RCM shortcomings, whilst still using core principles, e.g. streamlined RCM, Business-centred maintenance.	Improved performance through combining different elements e.g. use of detailed statistical analysis.	Often an oversimplification.	Second – Third
Customised	In-house developed or cherry picked from existing concepts for example focusing on value by combining elements of preventive, predictive, passive and proactive policies/actions.	Exploits the company's strengths and considers the specific business context.	Difficult to ensure consistency and quality in the concept developed. Requires continuous improvement.	Third

Table 4: Maintenance concepts

Source: Adapted from (Kobbacy & Murthy 2008)

2.4.3.1 *RCM: Condition-Based Maintenance (CBM)*

Reliability Centred Maintenance (RCM) recognises the close link between reliability and maintainability and has been developed in the aviation industry (Kim, 2010). Using RCM, the maintenance is carried out at component level using the failure mode effects analysis (FMEA) technique and reliability estimations of the system to create a cost-effective maintenance programme. However the principles of this method are difficult to imbed into other industries as it only assumes normal operating condition without considering continuous monitoring of important indicators that affect the degradation process in real life (e.g. load, operating conditions) (Kim, 2010).

The staple policy for the predictive maintenance within an RCM-based concept is Condition Based Maintenance (CBM), which similarly to PPM is widely talked about, however in this instance it is not a fully explored field in practice. The underlining theory of CBM is based on the belief that 99 per cent of equipment will evidence some sort of indicators prior a fault develops. Therefore according to the thorough examination of these signs an engineer can determine how severe the problem is and how long the machine can perform as normal without any actions being taken to repair the fault (Ahamed and Kamaruddin, 2012).

Consequently, according to the CBM theories, it is possible to identify the fault (detection), determine the root cause (diagnosis) and establish the severity and longevity of the equipment's optimum life (prognosis) through monitoring and evaluating of data collected through various techniques such as vibration, temperature, oil and acoustic analysis (Veldman et al., 2011a; Ahamed and Kamaruddin, 2012). Moreover, CBM is also able to verify where exactly the fault is, how quickly and to what extent the component is degrading (Veldman et al., 2011a; Veldman et al., 2011b).

The focus of research in the last decades within the maintenance field appears to be CBM orientated with the general conclusion that it *"is to be preferred above PPM and other policies"* (Koochaki et al, 2011, p.400) thus the literature relating to CBM is extremely widespread, and too numerous to extensively list within this review (as highlighted in the work of Jardine et al., 2006 and Ahamed and Kamaruddin, 2012).

However, generally the studies can be categorised into three areas namely technical (engineering related without any thought of the business aspects), computer and information science (focus on protocols of data/information exchange and different design in order to establish that investment is required for subsequently improving asset management) and finally, mathematical models and decision-making (i.e. the use of algorithms and stochastic models (e.g. Markov chain concept) to explain mechanical degradation) (Koochaki et al, 2011).

Companies can invest a lot of money in CBM and although implementation is successful from a technical perspective literature suggests that CBM is not always successful economically in practice (Koochaki et al, 2011; Veldman, 2011a; Lianghua et al, 2009). This may be due to the lack of managerial and operational impact consideration, as highlighted by Koochaki et al, (2011, p.399), the justification used to invest in CBM implementation *"do not often include the operational consequences"* and incline to "*mainly focus on a single piece of equipment*" thus lacking the overall vision required for successful delivery and benefit realisation. Furthermore, Muchiria et al., (2009) provide empirical evidence of alignment deficiency between managerial and operational KPIs and maintenance objectives from CBM implementation. Therefore, there is an evident need to undertake a comprehensive cost and feasibility analysis relevant to the context, prior to proceeding implementation of any CBM techniques (as highlighted by British Standards Institution, 2011).

On balance, consolidating the numerous maintenance management terminologies into actions, policies and concepts, enables a methodical schematic to demonstrate the holistic perspective of this young and dynamic management science. The maintenance concepts instruct the policies, and the policies stipulate the actions. Therefore the concepts appear to be transitional (first generation, to the most recent third generation). Moreover, the concepts can be linked to the relevant corporate strategies, which subsequently includes and impacts the tactical and operational elements of maintenance applications. Consequently, there is a substantial body of research promoting the latest third-generation concepts such as RCM-based CBM focused predictive maintenance policies, which recognises the relationship between reliability and maintainability based on data driven condition indicators to add value to the overall maintenance strategy.

Nevertheless, since majority of research appears to be focused on specific maintenance policies and actions, there is a gap, and an opportunity to investigate the impact of implementing a bespoke maintenance framework (concept, policy and action) within a new context such as the built environments Facilities Management (FM) component, which stipulates buildings maintenance management in harmony with the business strategy. For example, in such industry the most commonly applied concepts are first or second generation (i.e. LCC, Decision charts), therefore the resulting policies are predominantly Failure, Time or Usage-based (i.e. demanding preventative, reactive and precautionary actions). The next section will discuss these elements further and analyse the position of maintenance management in relation to FM within the built environment.

2.5 MAINTENANCE IN FM

2.5.1 FM: BACKGROUND AND OVERVIEW

FM started in the U.S in the 1970s, and ten years later the International Facilities Management Association (IFMA) was established with a goal to train and manage staff involved in the interface between workplace, staff and processes (Shah, 2007).

The FM function has many complex appearances and supply chains, for example the activities can be delivered by any combination of outsourced teams of external contractors (specialist), or a completely in-house team consisting of one or many personnel, or a mixture of the former and latter optimum nodes (Pitt, 2012).

FM as a business is considered as the most booming industry of the twenty-first century (Chanter & Swallow 2007) and one of the fastest growing specialisms in the UK (Barrett & Baldry 2003). Although the total market value is difficult to establish precisely, in the UK, a report by RICS estimated the market of FM in 2002 to be £94.9 billion, which appeared to be a thirty-five per cent increase since 1998. Furthermore, the report estimated that by 2007, the market value would exceed £100 billion (Chanter & Swallow, 2007).

Yet, FM as a function and profession is still considered to be in its youth (Barrett & Baldry 2003), consequently it is commonly and deceivingly viewed as the situation in which buildings and/or estates are managed, or a cost-centre that exclusively facilitates the reactive maintenance function or caretaking (Noor and Pitt, 2009a).

As an infant profession the scope, understanding and definitions of FM have been extensively debated throughout literature (Then, 1999; Nutt, 2000; Tay and Ooi, 2001;Noor and Pitt, 2009a). However, the dust around FM suffering an identity crisis (Tay and Ooi, 2001) appears to be settling with the British Institute of Facilities Management (BIFM) stating that the profession *“has come of age”* and defining it as *“the integration of processes within an organisation to maintain and develop the agreed services which support and improve the effectiveness of its primary activities”* (BIFM, 2015).

Similarly, IFMA defines FM as “*a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology”* (IFMA, 2015).

Both of these fairly generic definitions appear to be an amalgamation of concepts suggested throughout literature (Then, 1999; Nutt, 2000; Tay and Ooi, 2001; Pathirage et al, 2008; Noor and Pitt, 2009a; Jensen, 2009), and obliquely links to the value chain differentiating primary activities from secondary ones, reflecting Porter's (1980) generic competitive strategies.

However, according to Chanter & Swallow (2007) such definitions fail to reveal the dynamic operational facets and variety of services offered by FM service providers, which needs to be contemplated inclusively since they all assist in the successful management of assets within the built environment, as demonstrated in Figure 10.

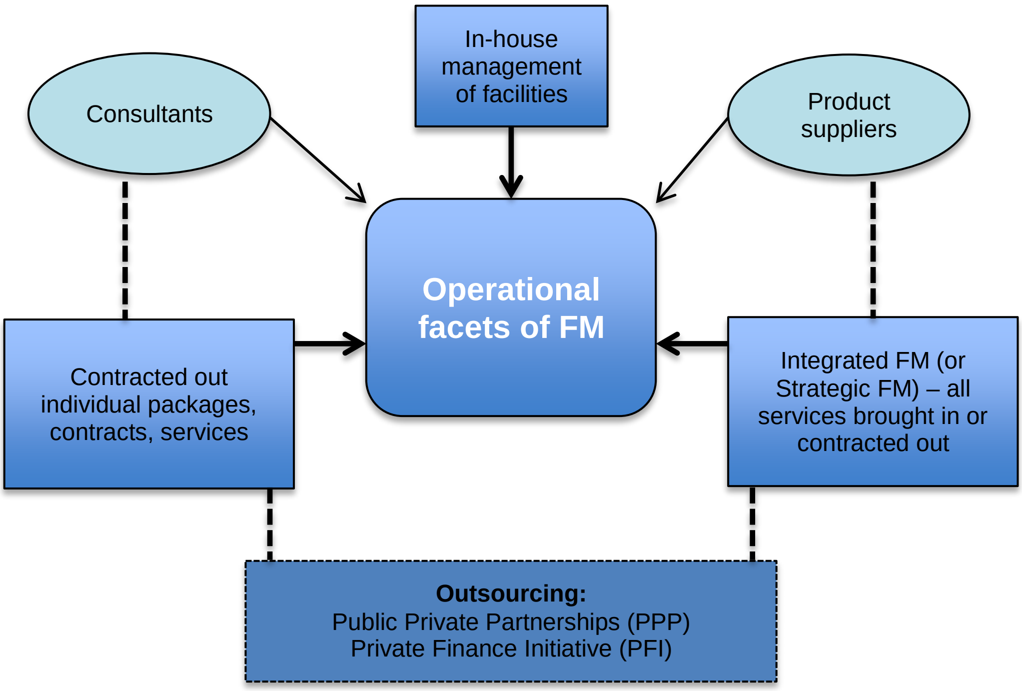


Figure 10: Distinct operational facets of FM

Source: Adapted from Chanter & Swallow (2007) and BIFM (2015)

Additionally, the services delivered within FM can depend on the contractual model and/or combination of models deployed by the organization (extensively discussed by Shah, 2007). Therefore, the operational facet and role of FM in managing the delivery of one or many of these services can invoke numerous variations of contracts and relationships, such the outsourcing features of PPP and PFI (Chanter & Swallow, 2007).

2.5.2 FM OUTSOURCING: PPP AND PFI

During the 1990s, in parallel with the expansion of the FM industry, there was a massive rise of FM outsourcing (via strategic or integrated FM). The outsourcing surge was reinforced by the emergence of Public Private Partnerships (PPP) created through Private Finance Initiatives (PFI) (Chanter & Swallow, 2007).

Although very similar, PPP is a generic term stating collaboration between public bodies and private companies, while PFI is a procurement tool used to finance private investment over a concession period (e.g. often more than twenty years). Under a PFI, the private contractor not only finances the design and build, but also operates and maintains the building. Through this arrangement the contractor fundamentally retains the operations and maintenance cost and risk by renting the finished project back to the public sector 'tenants' throughout the concession period (Chanter & Swallow, 2007).

PFI's have become the government's primary method used to revive the quality of public buildings such as schools, hospitals and defence buildings. As a result the notions of PPP and PFI are ingrained into majority of FM contracts where the efficient operations and maintenance of buildings are strategically intertwined with a contractor's vision to ensure the project is contractually and financially compliant through the lengthy concession periods (Chanter & Swallow, 2007; RICS, 2009; Shah, 2007).

In recent years, the substantial contractors output (over 36 per cent of construction output) has been one of the drivers behind numerous companies and contractors setting up FM business models with maintenance management as 'the core' element of the company's service provision with the vision of generating a profit through integrated cooperative partnerships (such as Skanska and their FM division). The European Union and its Public Procurement directives of Closed Competitive Tendering (CCT) and outsourcing have also influenced the growth these business models, since such models offer innovative ways to procure large portfolios of public property maintenance works which was previous unavailable to the private sector contractors (RICS, 2009).

2.5.3 MAINTENANCE EXPENDITURE

The 2009 RICS UK Practice Standards guidance notes on building maintenance (strategy, planning and procurement), states that the estimated the total maintenance expenditure in 2006 was £70 billion (5.4 per cent of Gross Domestic Product (GDP) (RICS, 2009). This estimation was based on the RICS Building Cost Information Service (BCIS) report. However, detailed analysis of the 2014 BCIS report seems to contradict these figures, as shown in Table 5, the total maintenance expenditure in 2006 appears closer to £50 million (3.66 per cent of GDP).

Year	GDP*	Total Maintenance Expenditure	Maintenance as % of GDP
2003	1,148,524	43,716	3.81%
2004	1,212,968	45,690	3.77%
2005	1,276,743	48,149	3.77%
2006	1,349,483	49,449	3.66%
2007	1,427,889	52,390	3.67%
2008	1,462,070	55,766	3.81%
2009	1,417,359	52,142	3.68%
2010	1,485,615	49,706	3.35%
2011	1,536,937	51,580	3.36%
2012	1,562,263	52,397	3.35%
** Gross Domestic Product, expenditure based measure at market prices from United Kingdom National Accounts.*			

Table 5: Maintenance Expenditure and GDP at 2014 Prices (£ million)

Source: (RICS 2014)

The purpose of the RICS BCIS report is to *'estimate the annual national expenditure on maintenance work on a consistent basis and to compare the results with the value of the stock to be maintained and the general level of national expenditure'* (RICS 2014, p.4). The 2014 report highlights 2012 expenditure to be slightly lower than the previous years brief respite (3.35 per cent of GDP). Furthermore, it makes the following key synopsis:

1. In 2012, the total spending on maintenance represented just 1.19 per cent of the value of the stock of the building and works maintained (at replacement cost), which was the lowest percentage observed for over 10 years.
2. The monies spent on all types of maintenance continued to fall significantly, for example the non-housing maintenance represents 1.25 per cent of replacement value of the stock of buildings and works to be maintained.
3. In contrast, the value of the Gross Capital Stock of building and works, based at 2010 prices, increased for the twenty-third successive year and is now valued at £4,266 billion.
4. The repair and maintenance output for Contractors' was 38.41 per cent of total construction output in 2011, which is a small increase following two years of relatively 36 per cent.

However, as stressed by Chanter & Swallow (2007), the work of maintenance departments is difficult to clearly identify, since there are complexities with definitions. Therefore, such statistics should be handled with caution.

2.5.4 FM OPERATIONS AND MAINTENANCE

In the UK, factors such as the booming PFI industry (with long-term contractual requirements) and a growing construction industry (part of the global market predicted to grow over 70 per cent by 2025) are driving the need to consider operations and maintenance elements as part of the whole life value of buildings (HM Government 2013; Chanter & Swallow 2007; RICS 2009). As a result the operations and maintenance of buildings is being recognised as one of the core competences of FM (IFMA, 2015), and key to sustaining the entire built environment and the nations aging building stock more effectively. In 2009, the IFMA 'Global Job Task Analysis' (GJTA) conducted a comprehensive survey of facilities managers in sixty-two countries. The analysis revealed eleven core competencies of FM as:

1	Communication
2	Emergency Preparedness and Business Continuity
3	Environmental Stewardship and Sustainability
4	Finance and Business
5	Human Factors
6	Leadership and Strategy
7	**Operations and Maintenance**
8	Project Management
9	Quality
10	Real Estate and Property Management
11	Technology

Table 6: Core FM Competencies

Source: IFMA (2015)

While FM has multiple capabilities, it is often undervalued (Lindkvist and Elmualim, 2010) and only few organisations understand the opportunities and contributions it has to offer (Alexander, 1997), such as participating in strategic decisions to reducing risks and gaining advantages on facility operations and maintenance issues (Nutt, 2002).

Similar to the evolution of maintenance, FM is transitional (currently fourth generation) and is no longer considered as an overhead managed at minimum cost, but a function that empowers core business by focusing on aligning building facilities and support service decisions with corporate strategies (Nutt, 2004; Osgood, 2004; Pathirage et al. 2008; McDonaugh and Nicols, 2009; Scupola, 2012).

As such, FM has become an integrated and strategic management approach (Pathirage et al. 2008) with the need to align business requirements and FM infrastructure being at the heart of any strategy that supports business success through managing and delivering the core services (IFMA, 2015; Then and Chau, 2012).

Evidently, the ‘old fashioned’ perceptions of FM as a management of cost-efficiency (Pitt and Hinks, 2001), or simply ‘reacting’ to building maintenance and caretaking is flawed (Noor and Pitt, 2009a). Such mindset fails to embrace the contemporary capabilities of strategic FM, which if supported at corporate level can not only combine resources from numerous activities of diverse disciplines (Noor and Pitt, 2009a), but also support and enhance a company’s strategic and operational activities (Goyal, 2007) resulting in significant opportunities of competitive advantage (Alexander, 1996; Puddy et al., 2001, Pathirage et al, 2008).

However, whilst there has been progressive, yet significant evolution and advancements towards accepting and initiating holistic strategic FM (as core business function that can provide competitive advantage), the competencies within FM (such as the delivery of services relating to buildings operations and maintenance) have been severely deprived of innovation towards the service delivery (Chanter & Swallow, 2007; RICS 2009).

Consequently, the body of knowledge relating to the operations and in particular maintenance of buildings assets, is not only limited but also pragmatically lags most industries (i.e. aviation, manufacturing, transportation, communication) (RICS 2009; Kobbacy & Murthy 2008; Chanter & Swallow 2007; Barrett & Baldry 2003; Alexander et al. 2004).

2.5.5 FM: ROLE OF MAINTENANCE MANAGEMENT

The context and management of maintenance is challenging enough in insolation, but this challenging endeavour is further enhanced in buildings maintenance particularly since all buildings operate dynamically convoluted assets with complex maintenance and data capture requirements that intertwine multiple disciplines (Chanter & Swallow 2007; RICS 2009). Hence empirical research is limited, consequently a lack of innovation in the domain (RICS, 2009; Pitt et al. 2006).

The maintenance of buildings have always been challenging, not just because buildings stocks are aging faster than being replaced, but also due to the consistently dynamic, yet demanding, context which requires multi-disciplinary skillsets to be balanced adequately with the constant business demands of reducing cost through limiting resources and time spent undertaking maintenance actions (Pitt et al. 2006; Chanter & Swallow 2007; CIBSE 2008; Lewis, 2006).

All buildings, subsequent to the construction phase and regardless of the quality of design and build, have an obligation to operate efficiently and effectively for decades. The process of FM maintenance management aims to firstly, help deliver the buildings operational expectations through ensuring that the engineering services are functioning safely and within the scope of the occupants' requirements (Pitt et al. 2006; Cibse 2008). Secondly, FM maintenance management attempts to ensure facilities are compliant with formal legislations and environmental policies, as well as third-party assessment and certifications (e.g. government's guidance relating to corporate social responsibility (CRS), health and safety offences act (2008)) (Pitt et al. 2006; Cibse 2008; Lewis, 2006).

Finally, FM maintenance is viewed as a methodology to preserve not just the economical value of whole building, but also the capital values of integrated assets (individual systems, components, and sub-components) (Pitt et al. 2006; Cibse 2008). Major plant replacements form part of the capital expenditure, which is usually programmed and budgeted as part of the whole building life cycle costs. In contrast, the operational expenditure includes minor parts replacements, spares inventory, energy consumption, and the resources necessary to undertake the process of building maintenance (Lewis, 2006).

2.5.6 FM: Maintenance Actions, Policies and Concepts

Figure 11 demonstrates the maintenance concepts, policies and actions in respect to FM strategy, FM policy and operations management. The FM strategy is usually aligned to, and complements the corporate strategy of the organisation. The most commonly utilised maintenance concepts seem to be mundane, limited and lacking customisation and/or RCM's predictive principles, as a result the most common policies practised tend to be failure-driven, time-based and/or usage-based maintenance delivered through corrective and/or preventive operations. There is extremely limited practical research and empirical evidence to demonstrate actual viability and applicability of predictive policies and actions in FM. Consequently, the industry application of predictive maintenance (condition-based maintenance) appears to be lagging other industries (Mobley 2002; RICS 2009; Chanter & Swallow 2007).

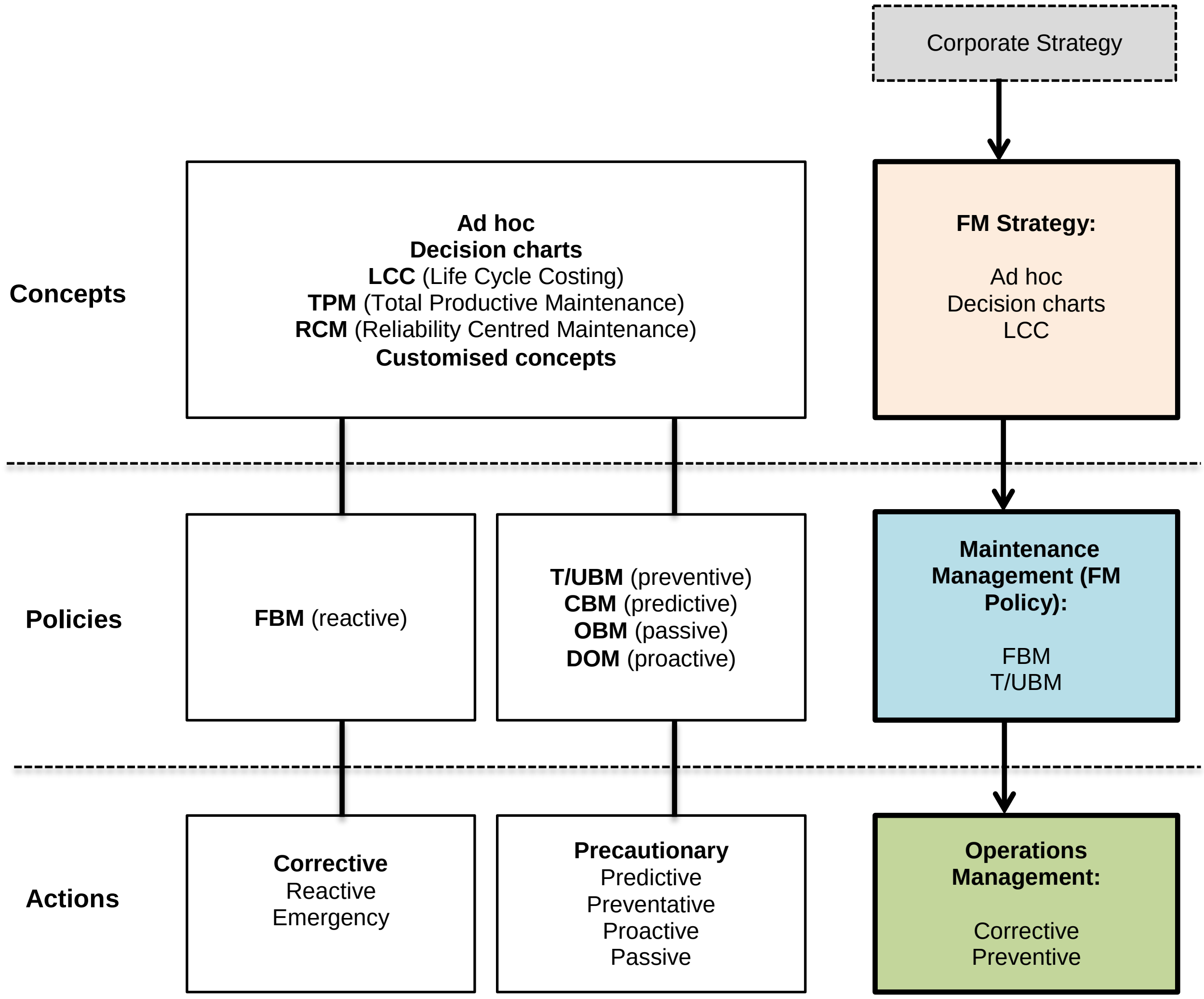


Figure 11: Maintenance actions, policies and concepts in FM

Source: Adapted from (Kobbacy & Murthy 2008; CIBSE 2008; RICS 2009).

2.6 SUMMARY OF OVERALL CONTEXTUAL POSITION

As emphasised by the research of Homberg et al., (2010), the critical necessity and ever-increasing significance of maintenance in the current digital society is evident across a whole spectrum of industries. Furthermore, effective management and adequate application of maintenance is often not given its due credit, yet the lack of maintenance is considered to have a direct association with an increased risk of failure (Wang, 2002). These failures are usually widely discussed and debated in the public domain (as demonstrated by the cases of AirAsia (BBC, 2015) and BP (Guardian, 2014; Telegraph, 2015). Therefore, inadequate maintenance has the potential to impact an organisation not only through loss of productivity and service, but also significant long-term reputational and environmental consequences.

Maintenance is not a new concept, and nor is the associated research interest. The literature surrounding various aspects of maintenance spans over fifty years. The studies undertaken by authors such as Martin (1994), Dekker & Scarf (1998) and Garg & Deshmukh (2006) highlight the categories, benefits, impacts, attributes and evolution of a discipline that is now considered by many as a young and dynamic multidisciplinary management science. For example, the research undertaken by Kobbacy & Murthy (2008) and Pintelon & Parodi-herz (2008) provide methods towards common terminologies and categorisation based on optimisation attributes. More recently, the work of Al-Najjar (2012), Ahmad & Kamaruddin (2012) and Zhu et al., (2015) builds on the beforementioned authors and delivers a holistic consolidation.

As a result of its evolution and versatile nature, the management context of maintenance is often incorrectly perceived as a simple endeavour (as stressed by Tinga (2010), Shin & Jun (2015). In reality, the numerous technical and administrative elements associated with maintenance management are complex and challenging to effectively manage. Therefore the role of the maintenance manager has become dynamic and is often based on intricate internal and external organisational influences (Garg and Deshmukh, 2006; Pintelon and Parodi-Herz 2008). Moreover, majority of the somewhat limited literature surrounding the management elements appear to focus on specific maintenance policies and actions, consequently there is a gap in research focusing on impacts of implementing bespoke maintenance frameworks that not only considers policies and actions, but more importantly explores concepts, which needs to be aligned to the business strategy. A domain within which the significance of this alignment is further reinforced is FM, where the strategies, tools and techniques involved in buildings maintenance management appear to be further convoluted and lagging behind other industries (Mobley 2002; RICS 2009; Chanter & Swallow 2007). For example, the effective application and implementation of innovative techniques such as CBM appears to be extremely limited within building maintenance management.

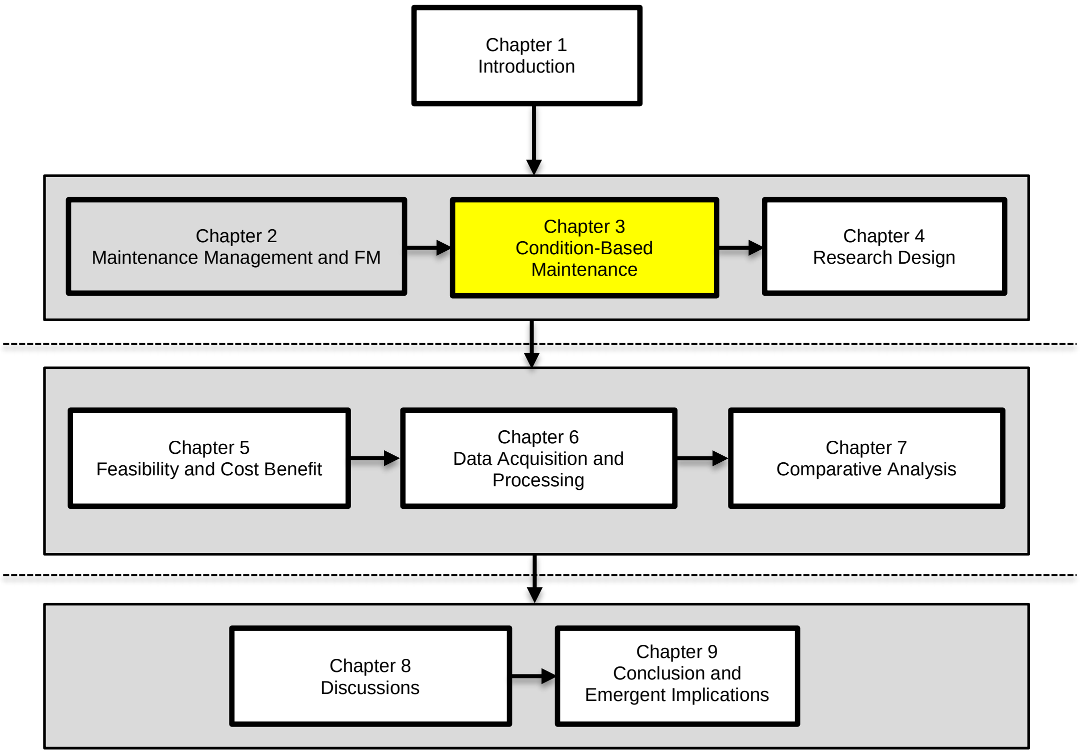
2.7 BOX 2: SUMMARY OF MAINTENANCE MANAGEMENT AND FM

This chapter provides the contextual foundations for the research, in summary:

- Maintenance is recognised as a significant aspect of ensuring availability, reliability and safety within a wide spectrum of industries. It requires attention on strategic, tactical and operational levels.
- The management of maintenance is a young, dynamic and multidisciplinary management science that is no longer considered as a necessary evil, but a cooperative partner that can generate a profit.
- However, the context of maintenance management is complicated by many challenges. For example multiple stakeholder involvement and a wide spectrum of technical and commercial issues, which all need to be considered and adapted accordingly to the organisations business goals of optimisation.
- The cost of maintenance is widely debated, yet the calculation of specific cost and its associated savings of optimisation continue to pose a challenge.
- A summary of maintenance actions (basic tasks), policies (set of rules) and concepts (tasks and rules in-line with business goals) is provided. The most evolved concept is 'Customised', which cherry-picks a variety of elements to enable core business strategy to be aligned.
- The key preventive policy (PPM) and predictive policy (CBM) are analysed. The focus of research in the past decade appears to be on CBM, yet practical application within some industries such as the built environment appears to be extremely limited, and preference is given to PPM.
- Finally, focus is put on maintenance in the context of FM within the built environment. Where, although the growth and significance of maintenance is evident, the management, effective application and implementation of innovative techniques such as CBM appear to be extremely limited.
- Evidence of predictive maintenance practices in FM is non-existent, thus FM appears to be lagging other industries.

The next chapter will supplement the context of the study by undertaking a detailed literature examination into CBM.

3 CONDITION-BASED MAINTENANCE



This chapter will provide a detailed review of CBM literature relevant to this study. It will critically discuss CBM advantages, disadvantage and research conducted using the most prevalent techniques towards achieving fault detection, diagnosis and prognosis. It will also analyse the application areas and availability of research relating to the built environment.

3.1 BACKGROUND

The first instigation of CBM is attributed to the Rio Grande Railway Company in the 1940s (Prajapati et al., 2012; Shin et al., 2015). The railway company monitored trends of temperature and pressure of engines to detect leaks associated with oil, coolant and fuel. Referring to the process as *'Predictive Maintenance'* the company achieved significant economical success in reducing unplanned engine failures. Moreover, they evidenced the intelligent identification of leaks and requirement to refill fluid levels proactively based on data analysis (Prajapati et al., 2012). Observing this success and realising the potential, the U.S Military became an early adopter of CBM techniques in maintaining military equipment. As a pioneer adopter, the US Air Force, defines CBM as *"a set of maintenance processes and capabilities derived from real-time assessment of weapon system condition obtained from embedded sensors and/or external test and measurements using portable equipment"* (Prajapati et al. 2012, p.388). Additionally, they further stress that *"the goal of CBM is to perform maintenance only upon evidence of need"* (Prajapati et al. 2012, p.388).

Similarly, Ahmad & Kamaruddin (2012, p. 140) state the function of CBM can be undertaken online (i.e. real-time) or offline (i.e. using portable devices), nevertheless the primary goal is to *"perform a real-time assessment of equipment conditions in order to make maintenance decisions, consequently reducing unnecessary maintenance and related costs"*. Furthermore, they stress that the implementation of CBM not only empowers improved equipment health management and reduces life cycle costs, but also helps avoid catastrophic failures.

Following the introduction of CBM and early adoption by the US Armed Forces, between 1950 and 1970, a distinct minority of other industries which have commonality of delivering maintenance requirements on high risk and high value assets (such as automotive, aerospace and manufacturing) slowly started to explore the ideas and applications of CBM as part of the maintenance strategy to demonstrate operational efficiencies and financial returns (Shin & Jun 2015; Prajapati et al. 2012). However, since the 1970's, the advancements of Information Communication and Technology (ICT) has accelerated the uptake of CBM technologies within public and private sectors (Holmberg et al. 2010). Consequently, nowadays CBM investment can be attributed to a higher number of large organisations such as the US Department of Defence, General Motors, Honeywell, GE, Honda and Digitech (Prajapati et al., 2012).

More recently, Shin & Jun (2015) carried out an in-depth literature review to discuss the definitions and relevant international standards, and subsequently present various case studies relating to the application of CBM. They stress that the rising interest in CBM has been driven by various emerging technologies including Radio Frequency Identification (RFID), Micro-Electro-Mechanical Systems (MEMS), Supervisory Control and Data Acquisition (SCADA) and Product Embedded Information Devices (PEID).

Whilst Shin & Jun (2015) do not provide details relating to what these technologies are, nor where they are specifically applied in the CBM context, they do surmise that such technologies could enable better data acquisition, processing and analysis on large datasets that are commonly associated with CBM, and consequently raise awareness of the potential benefits while reducing the documented limitations.

3.2 ADVANTAGES AND DISADVANTAGES OF CBM

The most significant advantages and disadvantages associated with CBM are reviewed below. Additionally, a summary of the prominently discussed advantages is provided in Table 7, while Table 8 highlights the disadvantages.

There are numerous advantages of CBM detailed in the literature, for example in relation to its superiority over other maintenance policies (Amin, 2013), CBM is believed to firstly reduce asset failure and downtime through its ability to detect and diagnose faults up to nine months prior to an actual failure (Shin & Jun 2015; Bernet 2011). Secondly, since conducting maintenance based on necessity is the core of CBM, it can reduce or eliminate unnecessary inspections and where time-based maintenance is applied it can reduce the interval frequencies thus avoiding over-maintenance (Shin & Jun 2015; Tinga 2010; Ahmad & Kamaruddin 2012). Thirdly, unlike other maintenance policies, CBM actions are usually based on asset data captured through condition monitoring therefore the data analysis enables faults to be determined with evidence and exactness. Moreover, following the detection of a fault the combination of data sources (e.g. trending, historic failures, operating parameters) reinforces and supports root cause analysis of underlying issues (Shin & Jun 2015; Jardine et al. 2006). Finally, as a result of CBM being deployed on a data and technology based foundation, it has the potential to be integrated with existing environmental controls infrastructures. However, successful integrations are seldom documented in the literature (Shin & Jun, 2015).

There are also several beneficial impacts of CBM in relation to the service delivery and operational components (Koochaki et al. 2011). Firstly, and most significantly, it can decrease the maintenance budgets since it enables efficient scheduling and reduction of unnecessary interventions. For example, the prevalent deployment of CBM in the U.S is estimated to have a savings in the region of $35 billion (Shin & Jun, 2015).

Secondly, it has the capability to increase safety while reducing and/or preventing disruption to service through early alarming of potentially serious faults and warnings relating to imminent failures (Jardine et al. 2006; Ahmad & Kamaruddin 2012; Randall 2011a; Prajapati et al. 2012;).
Thirdly, and consequently, it can improve overall customer satisfaction while enabling maintenance management stakeholders to reduce cost risk relating to dissatisfaction, service downtime and asset performance quality.

Finally, as a result of early detection, effective logistics planning can be achieved thus enabling the capability to optimise productivity and life of an asset before scheduling actions (Shin & Jun 2015; Veldman, et al. 2011a; Amin, 2013).

However, despite the numerous advantages of CBM, according to Shin & Jun (2015) upto thirty per cent of industrial assets do not achieve the benefits associated with CBM, which may be consequect of the documented disadvantages accompanying CBM. The first, and most prevalent disadvantage, is in relation to the high investment costs that are neccesary and challenging to justify. The overall costs can be broken down into four key components, namely the installation of data acquisition hardware (sensors), the cost of acquiring/developing software to conduct the analysis, staff training costs, and on-going support costs (e.g. replacement of sensors) (Shin & Jun 2015; Jardine et al. 2006; Al-Najjar 2012; Ahmad & Kamaruddin 2012).

Second, the implementation of CBM rarely inculdes management and operational support requirements and integration with buiness systems and processes, consequently the benefits associated with these elements are seldom documented or achieved (Shin & Jun 2015; Koochaki et al. 2011; Amin & Pitt 2014)

Third, neally all CBM literature is focused on single asset, technical case studies where the results demonstrated are based on experimental conditions (i.e. machine test-rigs), in contrast to large-scale plant wide practical implemenation. Therefore, the widely researched domain of CBM can be broadly categorised into three areas namely technical, computer and information science, and finally mathematical models and decision-making (Koochaki et al. 2011). Consequently, there is a discrepancy between the effects of CMB implementation reported in the literature and the actual effects experienced in practice.

Fourth, there are several limitations relating to the complex data, technology and necessary user competencies. For example, it is generally accepted that CBM generates large quantities of complex datasets; therefore without adequate training, knowledge and understanding there is a high possibility of misinterpretations (Jardine et al. 2006; Veldman, et al. 2011a). Moreover, since specific machine failure limits and/or fault thresholds can vary in reality, specialist fault detection and diagnosis training is usually necessary to understand, adapt and apply logical thinking (in conjunction with the International guidelines) based on the context of the environments (Holmberg et al. 2010).

Finally, the technologies and data analysis methodologies attributed to CBM are still considered to be in their infancy, consequently challenges exist in relation to precise quantification of savings, accuracy of diagnostics and establishment of impacts in reality (Shin & Jun 2015; Holmberg et al. 2010).

	Advantages of CBM
1.	Prior warning of imminent failure to inform actions that can reduce and/or prevent disruption to service delivery.
2.	In comparison to other maintenance approaches, CBM has increased chance of reducing asset failure and downtime.
3.	Increased precision in failure predictions – data analysis enables fault to be determined with exactness.
4.	Capable of increasing safety through early detection of potentially serious faults. This is particularly relevant safety critical industries such as Nuclear, Oil and Gas, as well as Aviation.
5.	Improves customer satisfaction through better service delivery and quality assurance capabilities.
6.	Enables maintenance management stakeholders to reduce cost risk relating to dissatisfaction, service downtime and asset performance quality.
7.	Maintenance management contracts generally require the service provider to ensure continuous, uninterrupted asset operations whilst evidencing maintenance to certify compliance towards warranties and overall service provisions. CBM promotes accurate evidence of applied maintenance.
8.	It enables effective maintenance and operations management planning and logistics planning relating to spares.
9.	Reduces or eliminates unnecessary inspections and over-maintenance.
10.	Where time-based maintenance is applied, CBM can enable the frequency intervals to be reduced based on condition evidence.
11.	It can decrease the maintenance budgets since it enables efficient scheduling and reduction of unnecessary interventions. For example, the prevalent deployment of CBM in the US is estimated to have a savings in the region of $35 billion.
12.	Enables the capability to optimise productivity and life of an asset. For example, regardless of a fault being present, as long as the asset operates the designated function within the pre-set performance limits, there is no requirement to overhaul or stop the operation.
13.	Enables easy and effective fault diagnosis through specific parameter and component monitoring. Also, asset event data such as historic failures and operating parameters can be combined to reinforce diagnosis.
14.	Aids Root Cause Analysis of faults by amalgamating numerous data sources and enabling problem elimination.
15.	It can be integrated with environmental and adaptive controls to facilitate process optimisation.
16.	It can provide significant energy savings due to effective consumption monitoring and efficient fault free operations of assets

Table 7: Advantages of CBM

Source: Adapted from various literatures (Shin & Jun 2015; Ahmad & Kamaruddin 2012; Prajapati et al. 2012; Veldman, et al. 2011a; Jardine et al. 2006)

	Disadvantages of CBM
1.	Almost 30 per cent of industrial assets do not benefit from the application of CBM.
2.	Majority of literature is focused on single asset case studies and/or ‘test-rig’ data, rather than large-scale plant wide implementation.
3.	Investment cost is necessary and usually substantial. This is attributed to several elements, including: - The initial necessity to install sensors and monitoring equipment to acquire data (hardware). - Further investment in software for analysis. - Training of staff to competently conduct the data analysis. - On-going support and maintenance of hardware and software (e.g. replacement of sensors).
4.	Implementations rarely include the management and operational support, requirements and integration.
5.	Produces large and complex datasets, which can be misinterpreted due to lack of training or noise within the complicated continuous data.
6.	Implementations require specialist fault detection and data collection devices, which are difficult to install and expensive to buy/replace.
7.	Where an offline system is used, periodic data collection creates the possibility of missing important events occurring between the intervals.
8.	Erroneous data acquisition where human input is required such as operating asset speed.
9.	Documented failure limits and/or threshold configurations can be unclear or different in reality.
10.	Technologies and data analysis methodologies are still in their infancy. Therefore, limitations exist relating to the accuracy of diagnostics application.

Table 8: Disadvantages of CBM

Source: Adapted from various literatures (Shin & Jun 2015; Ahmad & Kamaruddin 2012; Prajapati et al. 2012; Veldman, et al. 2011a; Jardine et al. 2006)

3.2.1 CBM ENERGY SAVING

As listed in Table 7, one of the advantages associated with CBM is the potential to provide energy savings as a result of efficient operations of assets. In the context of rotating assets (such as pumps, fans, motors and compressors) there is general agreement in the literature that the application of CBM to enable early fault detection, diagnosis and maintenance action contributes towards efficient operations, which results in energy savings (Rao 1993; Lee 2006; Gaberson & Cappillion n.d.; Saidur 2010; Luedeking 2015; Poór et al. 2014). This understanding is based on the foundation that assets operating with a fault consume higher amounts of energy.

However, the precise amount of energy attributed to CBM remains a subject of debate. For example, Rao (1993) suggests that the energy consumption in the UK could be saved by up to twenty per cent through the deployment of efficient monitoring and management such as CBM. In contrast, Lee (2006) reflects on the findings of industrial case studies focusing on maintenance activities and energy to state that the reductions associated with energy consumption can average between eight and 12.5 per cent.

Similarly, Gaberson & Cappillion (n.d.) investigated this notion comprehensively in relation to specific faults, i.e. misalignment and unbalance. They surveyed several research papers claiming an increase of up to fifteen per cent energy consumption is experienced consequent of these faults. However, based on their laboratory experiment using a 30-hp, 3-phase motor driving a 20kW generator, they concluded that 1.2 per cent increase in energy consumption was detected with misalignment (at 25 per cent power). Moreover, the increase in consumption as a result of unbalance was fifty per cent less than misalignment faults. This contradicts recent estimations of fifteen to thirty percent, for example by Katipamula & Brambley (2005) who claim such estimates are possible in commercial buildings applying CBM.

More recently, Saidur (2010) provides an in-depth review of motor energy analysis research that demonstrates the scale of energy consumption by motor driven systems (relevant to majority of buildings assets e.g. pumps, fans, air compressors), for example in the European Union motor driven systems account for an estimated sixty-five per cent of total electricity consumption. More specifically, in the UK the total energy consumed by motor driven system is approximately fifty per cent of total consumption. As a result, the cost associated with such energy consumptions are concerning to industries as well as government agendas relating to greenhouse gas emissions. Moreover, the significant lack of energy management and auditing relating specifically to motor systems may be contributing towards an increase in consumption rates. Therefore, Saidur (2010) and recently Luedeking (2015), suggest that better understanding relating to asset health and energy monitoring can enable efficient operations thus contribute towards an aggregated energy savings of between twenty and thirty-five per cent through out the asset life (i.e. 20 years). More specifically, systematic data driven energy audits are recommended to not only identify the losses and causes, but also to avert fails, improve overall performance and productivity, as well as reduce specific energy consumptions by approximately twenty to thirty per cent.

3.3 EXECUTION PROCESS

The goal of CBM is to inform maintenance management decision-making (Figure 12). This belief is supported throughout literature (see Ahmad & Kamaruddin, 2012; Jardine et al., 2006; Prajapati et al., 2012; Shin & Jun, 2015; Veldman et al., 2011a). Therefore, the execution process to achieve the 'decision-making' goal requires 'assessing equipment condition', or as highlighted in many literature (e.g. Ahmad & Kamaruddin, (2012) and Prajapati, Bechtel, & Ganesan, (2012)) the method of 'condition monitoring', which is the primary tool utilised in CBM to reveal condition of the monitored asset and can be defined as *"an activity which is intended to observe the actual state of an item"* (British Standards Institute, BS-EN 13306, 2010, p. 16).

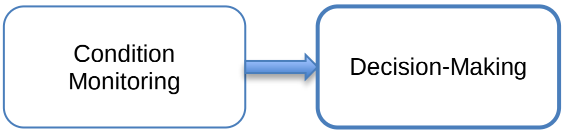


Figure 12: Goal of CBM

Source: Ahmad & Kamaruddin (2012)

While some authors (i.e. Ahmad & Kamaruddin (2012)) state that the general process of CBM simply starts with condition monitoring and concludes with decision-making. Others, expand beyond that, for example the research presented by Jardine et al., (2006) identified three steps required to execute a CBM system, namely data acquisition, data processing, and maintenance decision-making. Furthermore, Veldman et al. (2011a) suggest that the process requires an additional step, and consequently, they further developed this model by including a fourth step, implementation (as shown in Figure 13).

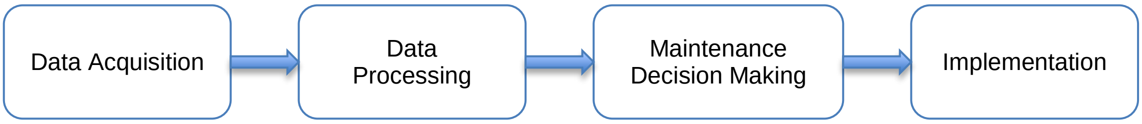


Figure 13: CBM execution model

Source: (Jardine et al. 2006; Veldman, et al. 2011a)

More recently, Shin & Jun (2015) used the mentioned foundations to also emphasise a similar process that firstly involves data gathering, secondly data analysing (which includes fault diagnosis and prognosis), thirdly decision-making at numerous management level, and finally actions such as repair, continue use with fault, or replace the asset. Therefore, it would appear that there is a common agreement on the overall process of executing CBM, consequently each of these steps will require further analysis and understanding.

3.3.1 ACQUISITION OF DATA

This is the first and essential step towards the execution of CBM as it refers to the collection and storing of useful data (Ahmad & Kamaruddin 2012; Jardine et al. 2006). This process is further elaborated by Jardine et al., (2006) as having two distinct data categories, firstly data captured through the process described as ‘condition monitoring’ and secondly the collection and storage of event data.

Event data refers to the information relating to incidents and actions that have been inflicted on the asset in question, for example preventive maintenance, breakdowns, installations, minor repairs, and servicing (Jardine et al., 2006; Veldman et al., 2011a).

Therefore, although the core of CBM data acquisition is achieved through specific add-on equipment, namely specialist wired and wireless sensors such as accelerometers to record vibrations (Holmberg et al. 2010; Shin & Jun 2015), there is an overall consensus that event data is not only necessary, but also uniformly important in CBM (Shin & Jun 2015; Prajapati et al. 2012). Moreover, Jardine et al. (2006) categorically stress that the collection of event data and condition monitoring data are equally important in CBM, particularly because people appear to be putting more weight on the condition monitoring data and neglecting the event data. While there are usually large quantities of event data available from everyday control systems and maintenance recording protocols, the reluctance towards its CBM usage may be consequent of manual recording or time-consuming collection process that generally requires a human (Jardine et al., 2006).

However, majority of literature (such as Jardine et al., (2006), Veldman et al., (2011a) and Prajapati et al., (2012)) fails to address several fundemental steps that are necessary prior to data acquisition, and although Shin & Jun (2015, p. 126) briefly mentions that *‘...it is imperative to define the business model for new maintenance operation and identify benefits and costs’* – it is not as comprehensively detailed as for example in Mills (2011) and ISO 17359 (British Standards Institution 2011).

The international standard for Condition Monitoring and Diagnostics of machines – General Guidelines (BS ISO 17359:2011), first issued in 2003 and recently reviewed, provides a execution framework that covers nine different types of machines (including pumps, fans and motors) and documents the fault examples including modes of failure with related symptoms and measurement considerations (Mills, 2011). As shown in Figure 14, taking the best practice guidance on board when implementing CBM can prevent wrong techniques being applied thus wasting time, money and resources without any effect on operations or equipment availability (Mills, 2011). Furthermore, the ISO guidelines emphasise five key steps to be undertaken <u>before</u> data acquisition.

Firstly and most significantly, it is recommended to conduct a cost/benefit and feasibility analysis, which not only enables determining of accurate key performance indicators, but also establishing of the technical and economical viability, as well as defining the benchmarks to measure the effectiveness of CBM.

Consequently, there are several key items to consider in this analysis including the overall cost of lost production, life cycle costs, consequential damage, warranties and insurances (British Standards Institution, 2011).

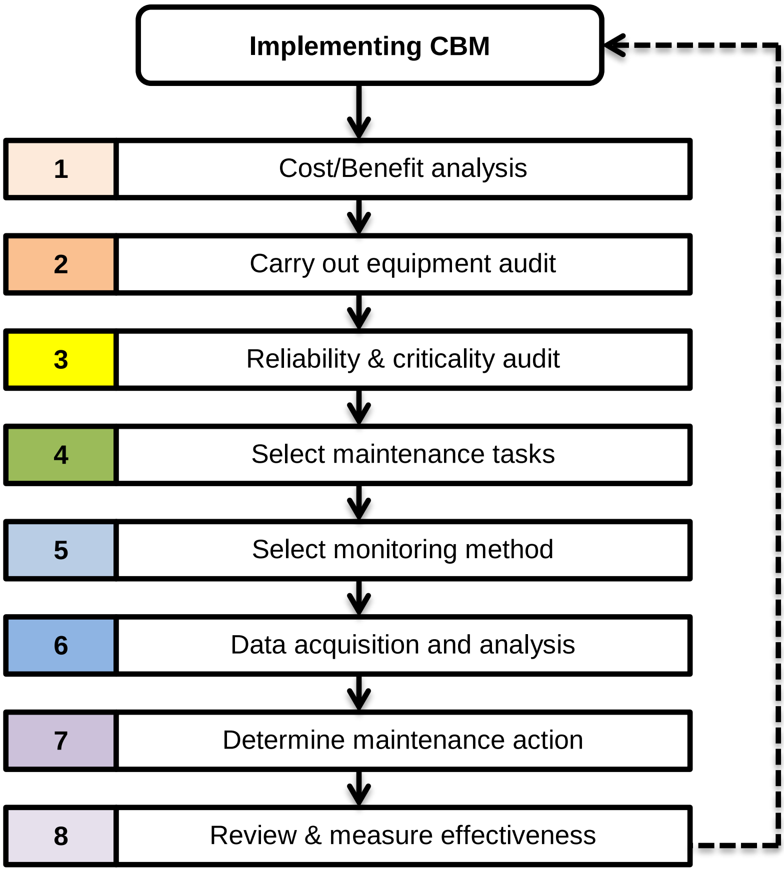


Figure 14: CBM Execution Schematic based on ISO 17359

Source: Adapted from Mills (2011) and (British Standards Institution 2011)

Secondly, subsequent to the cost/benefit analysis, it is advised to conduct an equipment audit in order to establish the exact components, processes and equipment to be monitored and data to be captured. Moreover, it is important to determine the function of the equipment during this audit and ensure understanding is captured relating to *'what the system, machine or equipment is required to do'* and *'what the machine or system operating conditions or range of operating conditions are'* (British Standards Institution 2011).

Thirdly, a reliability and criticality audit is recommended to develop a prioritised list of assets that require inclusion and exclusion of CBM. Moreover, it is suggested that a reliability block diagram is created and a rating system is utilised to determine the overall criticality based on factors such as redundancy, cost of downtime, life cycle costs, safety and environmental impacts, as well as cost of the monitoring system and failure rates. Additionally, further detailed analysis into the faults, symptoms and potential measuring parameters (that would indicate the presence or occurrence of faults) should be carried out through failure modes and effects analysis (FMEA) or failure mode effect and criticality analysis (FMECA) (British Standards Institution 2011).

Fourthly, the maintenance actions or tasks to be carried out require deliberation. Parallel to this, alternative maintenance policies are suggested to be considered in the event that the asset is categorised as critically requiring inclusion in the CBM programme, yet the failure modes associated with asset do not have a measurable symptom. Such polices can included the application of corrective and/or preventive maintenance actions, running asset to failure or considering modifications (i.e. through the designing out protocols) (British Standards Institution 2011).

The final step recommended prior to data acquisition is the exhaustive process of determining the monitoring methodologies to be used. In this step, there are ten components that require attention, as described in Table 9. All of these considerations contribute towards the successful execution of CBM, therefore it is recommended that adequate consultations of appropriate international standards and industry specialist takes place to ensure greater chance of CBM implementation success (Mills, 2011).

Taking all these data acquisition elements into consideration, there appears to be overall agreement that the acquisition of both condition monitoring data and asset event data are important in CBM. However, there appears to be a gap in the literature discussions relating to best practice steps that are recommended before the acquisition of data, for example the CBM execution model discussed by Jardine et al., (2006) and subsequently refined by Veldman et al., (2011a), starts the process with ‘data acquisition’ and ends with ‘implementation’ of an action.

Therefore, although relevant international standards (particularly ISO 17359) discuss these key steps comprehensively, prominent literature on CBM execution (e.g. Shin & Jun (2015), Jardine et al., (2006), Veldman et al., (2011a)) fails to emphasise these necessary pre data acquisition steps. Consequently, it could be argued that such shortfall in promoting the undertaking of a comprehensive technical and economical feasibility (before data acquisition), may be contributing towards the limited success rates attributed with CBM implementation (as highlighted by Shin & Jun (2015)). Moreover, the guidance execution schematic provided by ISO 17359 appears to be far more robust than the models put forward by Shin & Jun (2015), Jardine et al., (2006) and Veldman et al., (2011a).

Monitoring Method Consideration	Description
Measurement technique	There are twenty-seven technique described, one or more measurement technique may be appropriate (e.g. current, voltage, vibration). The measured parameters can be simple measurements or overall values or overall averaged over time. However, certain simple measurements of overall values may not be sufficient to show the occurrence of fault, further analysis will be necessary therefore other relevant standards should be consulted.
Accuracy of monitored parameters	Methods using trending of values can be effective where repeatability of measurement is more important than absolute accuracy of measurement.
Feasibility of monitoring	Considerations are necessary regarding the general and technical feasibility of acquiring the measurements, including ease of access, complexity of the required data system, safety, cost and level of processing that will be required after acquisition.
Operating conditions during monitoring	The actual monitoring (if possible) should be conducted when the asset has reached a predetermined set of operating conditions (e.g. normal operating temperature, or speed). A baseline should be established and subsequent measurements compared against that baseline using trending to highlight fault development.
Monitoring intervals	Continuous or periodic sampling and capture of data. Intervals will depend on and be influenced by several factors such as operating conditions of duty/standby cycles, cost and criticality of assets. These considerations should be accounted in the initial cost/benefit analysis.
Data acquisition rate	For steady-state conditions, the data acquisition rate should be fast enough to capture a complete set of data before conditions change. Higher speed data acquisition may be necessary for transient conditions. Further ISO guidelines should be consulted (e.g. ISO 13373-2).
Record of monitored parameters	Additional information relating to the monitored parameter should be recorded, for example, essential data about asset, operating conditions, measuring positions, measured quantities and units, data and time.
Measuring locations	Measuring locations should be chosen to give the best possibility of fault detection, labelled uniquely and identified with several considerations for example safety, accessibility, environment, cost, sensor selection, signal conditions and repeatability of measurements. Further ISO guidelines should be consulted for detailed analysis (e.g. ISO 13373-1).
Initial alert/alarm criteria	Initial alert/alarm criteria should be configured to provide earliest possible indication of the occurrence of fault. May require amendments based on asset specific factors. Further ISO guidelines should be consulted for detailed analysis (e.g. ISO 13373-1, ISO 10816 and ISO 7919).
Baseline data	This is asset operation data captured when the operation is acceptable and stable, subsequent data is compared against this.

Table 9: Items to consider for establishing the monitoring methods

Source: British Standards Institution (2011)

3.3.2 PROCESSING AND ANALYSING DATA

Once the data has been collected it is then cleaned (which is an important and complicated task) and analysis is carried out using appropriate software tools, algorithms, or models (e.g. statistical and/or analytical) (Jardine et al. 2006; Shin & Jun 2015). As shown in Table 10, condition monitoring usually acquires the following types of data: value (i.e. single value such as temperature, pressure and humidity), waveform (e.g. vibration and acoustic data) and multi-dimension (e.g. visual images, thermographs etc.).

The data can be processed and analysed in several ways, from carrying out simple direct comparison or trending, to more sophisticated statistical means which take account of historic data. Examples of such methods for signal processing (waveform and multi-dimension data types) include frequency-domain analysis, waveform analysis, and time-domain and time-frequency analysis (Jardine et al., (2006). Alternatively analytical models can be utilised to determine cause-effect type expressions of failure.

Three categories of condition monitoring data:	
Value Type	Data collection at a specific time epoch for a condition monitoring variable are a single value. For example, oil analysis data, temperature, pressure and humidity are all value type data.
Waveform type	Data collected at a specific time epoch for a condition monitoring variable are a time series, which is often called time waveform. For example vibration data, acoustic data are waveform type.
Multidimensional type	The most common multidimensional data are image data such as infrared thermographs, X-ray images, visual images, etc.

Table 10: Three categories of condition monitoring data
Source: Jardine et al., (2006)

The processing and analysis of the acquired data enables the concepts of mechanical fault detection, diagnosis and prognosis, which are important features of CBM (Schwabacher, 2005; Jardine et al., 2006; Veldman et al., 2011; Ahmad and Kamaruddin, 2012). Therefore, the analysis of CBM data to inform decision-making has two parts, namely diagnostics and prognostics (Jardine et al., 2006; Shin & Jun, 2015).

The objective of fault diagnostics, which is triggered after a specific measurement shows a potential problem, is fault detection, isolation and subsequently fault identification (Jardine et al., 2006; Shin & Jun, 2015). Prognostics on the other hand is a new term developed by the scientific community to tackle diagnosis and prognosis together (Shin & Jun, 2015). It is used to predict the health condition and occurrence of fault before it occurs and can be defined as the process of *"detecting the precursors of a failure, and predicting how much time remains before a likely failure"* (Schwabcher 2005, p.1).
The process of posterior event analysis (diagnostics) and prior event analysis (prognostics) can be (individually or together) utilised as part of a CBM system in order to reduce failures through interventions before occurrence of an actual fault (Jardine et al., 2006; Veldman et al., 2011a). Although

individually prognostic is believed to be more efficient at achieving the core objective of undertaking CBM (zero-downtime), diagnostics is necessary not only to enable prognostics, but also when predictions fail (common in practice) and a fault transpires the application of diagnostics is required (Jardine et al., 2006; Veldman et al., 2011a; Ahmad and Kamarurddn, 2012).

Based on the comprehensive survey conducted by Jardine et al., (2006) and subsequently by Veldman et al., (2011a), it would appear that the most common methods of diagnostics seem to be either statistical analysis based, artificial intelligent (e.g. neural networks, fuzzy-logic) or models based on explicit physics and mathematics approaches. Similarly the *'hierarchy of prognostic methods'* (Figure 15) put forward by Lebold and Thurston (2001) can be used to classify the prognostics methods into three main approaches, namely experience-based, evolutionary (also called data-driven in Schwabcher (2005) and Tobon-Mejia et al., (2010)) and model based. In that order, the each method increases the level of accuracy, as well as the complexity and development efforts.

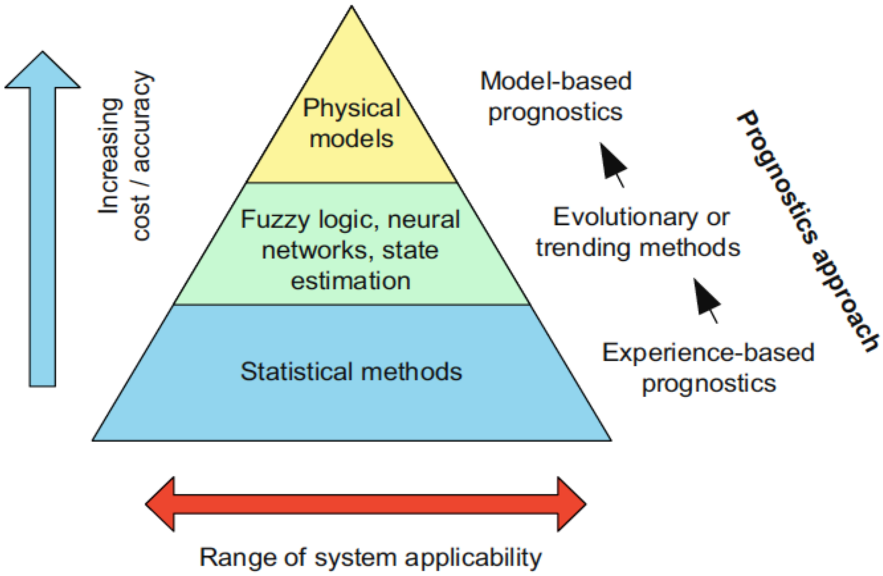


Figure 15: Hierarchy of prognostic methods
Source: Lebold and Thurston (2001)

3.3.2.1 Experience-based

Although these methods are based on simple reliability functions such as Exponential Law and Weibull Law rather than complex mathematics to predict the Remaining Useful Life (RUL) or time to failure, the methods require extensive experience data (e.g. operating, failure and maintenance) to be collected over a significant period of time. Additionally, the results from these methods are not as accurate as the other two approaches (Tinga 2010; Jammu & Kankar 2011).

3.3.2.2 Evolutionary (or Data-Driven)

In these methods data acquisition is carried out via real-time sensors, then the data is processed based on different models and/or statistical tools such as neural networks, fuzzy-logic or Bayesian networks (Tinga, 2010; Jammu and Kankar, 2011). The processing of data can develop a degradation model as well as estimate the future health state and RUL of the monitored asset, for example, Gebraeel et al. (2004) used artificial neural network based models to predict bearing failures and establish that the weighted average of the exponential parameters gives the best prediction of bearing failure times.

Similarly, Si, Wang, Hu, & Zhou, (2011) undertook one of the most extensive literature surveys of data-driven approaches and concluded that further investigation is necessary in the key areas including the concept of data fusion (multi-dimensional monitoring inputs), influence of external environmental variables, and models that can deal with multiple faults, as well as those based on few or no historic data.

3.3.2.3 Model Based

These methods simulate the degradation process using physical models and failure mechanisms and are considered the most sophisticated prognostic approach according to Tinga (2010). However this is disputed by Jammu and Kankar (2011) who state that data-driven (evolutionary) approaches have an advantage over model-based and experience-based methods since it is easier to acquire reliable data from within industry than it is to construct physical or analytical behavior model.

On balance, the state of the art processing and analysis of CBM data through the methods of diagnostics and prognostics is widely discussed in the literature, particularly relating to specialist industries such as Aerospace industry. However, the practical applications of such research within industry is still limited, for example, Schwabcher (2005) highlights the importance and practical usage of fault detection, diagnosis and prognosis from the perspective of spacecraft reliability as utilised by NASA (National Aeronautics and Space Administration). Having conducted a literature survey relating to data-driven and model-based fault detection, diagnosis and prognosis, Schwabcher accomplishes that there has been a greater degree of progress with detection and diagnosis than in prognosis.

However, regardless of specialist industry focus research and lack of practical applications, both methodologies have been theoretically demonstrated to be extremely valuable concepts of CBM, especially the data-driven models as highlighted by the comprehensive reviews undertaken by (Si et al. 2011) and Schwabacher (2005).

CBM phase	Data processing	Diagnostics	Prognostics	Maintenance operations
Data processing techniques	Kalman filtering Time–frequency/ time–frequency moments Wavelet analysis Autoregressive (AR) model Fourier analysis Wigner–Ville analysis Fuzzy logic Artificial Neural network Genetic algorithms Statistical pattern recognition Hidden Markov model Support Vector Machine Decision tree induction	Logistic regression Artificial Neural network Reliability theory Statistical analysis (e.g. Regression) Time series data analysis	Case Based Reasoning (CBR) Renewal theory Math programming Simulation	Multi-Criteria Decision Making (MCDM)

Table 11: CBM data processing techniques
Source: Shin & Jun, 2015

Nevertheless, while there are numerous documented techniques available for data processing, diagnostics and prognostics (as summarised in Table 11), there appears to be two key challenges in moving the methodologies into practice. First, the research is sophisticated and usually undertaken in laboratory settings that only involves a single '*test rig'* without considerations towards multiple assets, or the operating environment (Koochaki et al. 2011; Schwabacher 2005), and second there is a need to shift focus from isolated technical solutions to the creation of tools that can be integrated into existing business models and support management decision-making protocols (Koochaki et al. 2011; Shin & Jun 2015).

3.3.3 CBM MANAGEMENT: DRIVERS AND BARRIERS

Based on the processing of data a diagnostic and/or prognostic decision is provided by the CBM system, which can be a vital factor on a maintenance personnel's decision to undertake maintenance (Jardine et al., 2006; Prajapati et al., 2012). The decision-making is usually preceded by some form of action being implemented, which can include planning and executing an intervention, as well as producing evaluation reports to inform lessons learnt (Veldman et al., 2011a).

However, despite the fact that the literature around CBM illustrates the topic mainly in the light of technology (Koochaki et al, 2011), the barriers, drivers and success factors for the CBM implementation seem to originate from the operational and management decision-making side such as risk reduction, optimised use of resources, efficiency gains, and improved maintenance processes (Amin & Pitt, 2014). It can be therefore deducted that CBM adoption cannot be employed in isolation from plant organisation but must be integrated within the entire facility management and operation (Koochaki et al. 2011; Prajapati et al. 2012; Amin & Pitt, 2014).

Maintenance accounts for one of the biggest proportion of the facility operation spending. It used to be considered as a 'necessary evil' where the costs could not be avoided or reduced. However the technological development along with the managerial and operational drive towards maximisation use of assets became biggest motivation for the organisation to implement CBM (IAEA, 2007; Amin & Pitt, 2014).

However such a major change from the traditional preventive maintenance to more proactive CBM significantly impacts managerial and operational processes, which are subjected to both change management as well as culture change. These require endeavour of both staff and management directly affected by the change but also the entire supply chain (IAEA, 2007). Such joint effort translates to the list of the success factors for CBM implementation.

The first aspect suggested by the explored literature is full commitment of staff to the process and the use of new technology as well as management and the supply chain in procuring for the appropriate technology and training provision (IAEA 2007; Koochaki et al. 2011; Prajapati et al. 2012). Second critical success factor evidenced by the literature is participation of all the parties involved and confidence in positive outcome of the transition which must be reiterated by the lead management. Further, holistic approach must be applied throughout the entire facility. Finally, in order to ensure maximised long-term decision-making benefits of CBM, sustainable programme implementation must be put in place. This means the staff must be regularly trained, resources dedicated to the task must be made available at all times and the process must be granted with the management continuous support (IAEA, 2007).

Overall in practice, since the process is not mandated, the management role, and leadership of the CBM implementation as well as involvement of the entire supply chain are vital to drive the process forward (Veldman et al., 2011a).

Furthermore, the literature suggests supply chain is also responsible for creating value, which in maintenance and new process implementation is essential (Pitt et al., 2014). Supply chain management (SCM) has multiple definitions; Lambert (2004) however identifies it as *an integration of key business processes across the supply chain for the purpose of creating value for the customers and stakeholders*. The critical components of SCM are strategic purchasing, supply management, supplier base reduction, and communication where two-way information sharing is fundamental to support FM processes (Noor & Pitt, 2009). When considering introduction of a new product or an innovation process, the supplier involvement becomes an instrumental factor in its successful implementation, which can proof to be beneficial to all partners involved from the perspective of cost efficiencies, rapid production cycle, better product quality and access to technological advancements (Noor & Pitt, 2009a). Such collaborative innovation can encompass elements of process innovation management and product management within a network structure where neither partners could deliver on their own meeting same expectations for product quality delivery and overall cost. Researchers suggest that collaborative innovation brings integration of all relevant aspects of knowledge, technology, process and relationship management as a result creating value (Noor & Pitt 2009b).

The conclusive driver in the literature for CBM implementation is a drive toward quality and innovation which have been incorporated within strategies of all the ambitious organizations wishing to cut competitive edge not only with the cost but service delivery (IAEA, 2007). Such approach focuses not only on quality but also availability, reliability, post-delivery service as well as delivery performance (Noor & Pitt, 2009a). Innovation on the other hand takes shape of more exploratory investment, where the organization learns from its past mistakes and examines the outcome of the project that can prove to be somewhat beneficial (Noor & Pitt, 2009a).

Finally, similarly to drivers and success factors, barriers for CBM for implementation relate not only to technological challenges but also operational and managerial ones and include economic justification, training, change management plan, use of resources as well as closely correlated culture change (IAEA, 2007; Pitt et al., 2014). Therefore, in order to minimise them, the best practice guidance and recommendations from the various sources including relevant international standards, should be considered in process of CBM implementation.

3.3.4 ISO STANDARDS

In conjunction with the vast amounts of literature in the field of CBM, there are now numerous international standards available to support the approach throughout the execution processes. Shin & Jun (2015) provide a survey of the significant standards, shown in Table 12.

The CBM related standards vary from general guidance on execution (e.g. ISO 17359), to technical guidance on processing and analysis of vibration based conditio monitoring (i.e. ISO 13373-2). Furthermore, while some cover the general machinery industry in relation to condition monitoring and diagnositc (such as ISO 13372, ISO 13373, ISO 13380, and ISO 13381), others are more specific for example documenting mechanical vibration and shock associated with condition monitoring in ISO/TC 108, and ISO 14224 reflecting the interest and uptake of CBM policies within the plant engineering industries such as petroleum, petrochemical and natural gas. Additionally, to enable standardisation and compatibility ISO 13374 documents the formats and methods for communicating, presenting and displaying relevant information and data (Shin & Jun, 2015).

Standards	Subject / description
IEEE 1451	Smart transducer interface for sensors and actuators.
IEEE 1232	Artificial Intelligence Exchange and Service Tie to All Test Environment.
ISO 13372	Condition monitoring and diagnostics of machines—Vocabulary.
ISO 13373-1	Condition monitoring and diagnostics of machines: Vibration Condition Monitoring—Part 1. General Procedures.
ISO 13373-2	Condition monitoring and diagnostics of machines: Vibration Condition Monitoring—Part 2. Processing, analysis and presentation of vibration data.
ISO 13374	MIMOSA OSA-CBM formats and methods for communicating, presenting and displaying relevant information and data.
ISO 13380	Condition monitoring and diagnostics of machines: General Guidelines on using performance parameters
ISO 13381-1	Condition monitoring and diagnostics of machines: Prognostics general guidelines
ISO 14224	Petroleum, petrochemical and natural gas industries-collection and exchange of reliability and maintenance data for equipment.
ISO 17359	Condition monitoring and diagnostics of machines—General guidelines
ISO 18435	MIMOSA OSA-EAI diagnostic and maintenance applications integration
ISO 55000	Asset management
ISO/TC 108	Mechanical vibration, shock and condition monitoring

Table 12: Survey of CBM international standards

Source: adapted from Shin & Jun (2015)

3.4 CBM METHODOLOGIES

The ISO 17359 provides twenty-seven different condition monitoring and performance considerations including vibration, temperature, ultrasonics, oil, and acoustic emission (se Appendix I). However, the most commonly discussed techniques are vibration monitoring, acoustic monitoring and lubricant monitoring (Ahmad and Kamaruddin, 2012; Mills, 2011; Randall, 2011a).

3.4.1 VIBRATION

Vibration monitoring is the most frequently applied and extensively discussed condition monitoring technique that is incorporated into CBM policies to enable predictive maintenance (Randall 2011a; Ahmad & Kamaruddin 2012), consequently section 3.5 is dedicated to exploring this technique further.

3.4.2 ACOUSTIC MONITORING

The monitoring of sound or acoustics is also a technique often used for CBM and while the time-series data and signal processing are similar features to vibration monitoring, the two techniques have fundamental differences. For example, as stressed by Ahmad & Kamaruddin (2012) acoustic sensors 'listen' for acoustic emission (AE) coming from the asset, in contrast to vibration sensors (accelerometers) which are externally mounted to acquire local intrinsic motions. Since most CBM applications are undertaken within enviroments considered to be 'noisy', one of the fundamental challenges with AE is the filtering and issolation of sounds relevant only to the monitored asset and not the externally generated environmental noise or AE from other machines (Tandon & Nakra 1992; Mirhadizadeh & Mba 2009; Randall 2011a).

3.4.3 LUBRICANT MONITORING

The analysis of oil (commonly referred to as lubricant monitoring) can be utilised to determine the quality (or condition) of the oil within an asset. Based on the analysis, it is possible to establish the presence of a fault based on wear particles/chemical contamination (i.e. safeguarding the component involved) and the suitability of the oil for further use (i.e. safeguarding the oil quality) (Ahmad & Kamaruddin, 2012).

According to Randall (2011a), there are three categories of oil analysis, namely chip detectors, spectrographic oil analysis procedures (SOAP) and ferrography. Chip detectors are devised to retain debris that is present in a circulating lubricant system to enable periodic analysis without the need to extract the lubricant. Similarly, ferrography allows a more detailed analysis through microscopic investigation of debris captured magnetically. In contrast, the use of SOAP does mandate the requirement to sample regularly and conduct spectrographic chemical analysis (Randall, 2011a).

3.4.4 OTHER METHODS

Other monitoring techniques such as the use of asset performance analysis and infra-red (IR) thermography (visual display and measuring of temperature change on assets) have been discussed in the literature (Randall 2011a; Beebe 1987; Wallace & Prabhakar 2003). However due the limitations such as reliability and practicality deficiencies (compared to other techniques) they have not had much promotion for use on their own, consequently they tend to be used as supplementary methods (Beebe 1987; Randall 2011a).

Therefore, this research utilises the most robust and prevalent method of vibration condition monitoring and analysis (as mentioned in 3.4.1.), this is further detailed below.

3.5 VIBRATION ANALYSIS

Excessive machine vibration is known to reduce the efficiency and life of an asset while increasing the chances of breakdowns and associated energy consumptions (Kutin, 2009; Wilson, N.D). As a result, it is accepted that for machinery such as pumps, fans and motors, vibration condition monitoring and analysis is one of the most appropriate techniques (Rajan and Roylance 2000; Watts 2009; Bernet 2011; Pump-zone, 2012).

The concept of vibration analysis on machines (also referred to as ‘mechanical signature analysis’) has been around for decades, for example (Mitchell & Capistrano 2007) provides a comprehensive review of ‘seventy years of continuous progress’ in the field of vibration measurement and analysis. The technique is commonly linked to mission critical machinery utilised by specialists and government agencies capable of justifying high expenditure on maintenance. However, as a result of recent developments in vibration sensors, and technologies for data collection, storage and analysis, this solution is now opening up to smaller organizations (Bernet 2011; Holmberg et al. 2010), consequently leading to better asset performance, increased asset life and substantial energy savings as highlighted by Davis (2010).

The fundamental theory behind measuring and analysing machine vibrations is based on the fact that all machines (especially rotating machines such as pumps, motors and fans) have a certain vibration signature when operating under normal 'health' conditions, and the occurrence of a fault on the machine alters that signature (Randall 2011a; Berry 1997; Randall 2011b; Shreve 1994). Furthermore, since each fault impacts the 'normal' signature patterns in a distinct way, by measuring and analysing the changes and establishing the fault frequencies (frequencies generated by a specific fault), it is possible to distinguish vibration signatures that relate to faults (Randall 2011a; Berry 1997; Randall 2011b).

Therefore, excessive vibration from a rotating asset is usually consequent of mechanical issues such as imbalance, misalignment, looseness and bearing faults (Kutin, 2009; Cotoz, 2012). Although all rotating assets vibrate to some degree of intensity throughout the lifecycle, the vibration levels can provide an indication of its condition (Kutin, 2009). Consequently, using vibration analysis it is possible to determine the source/cause and establish normal acceptable vibrations from harmful levels.

Moreover, one of the key advantages associated with vibration analysis is the potential to detect a fault or failure earlier than other condition monitoring techniques such as lubricant analysis and thermography. As demonstrated in Figure 16, the occurrence of an asset failure can be detected in the changes in vibration up to nine months before an actual failure transpires. In contrast, the presence of debris in oil (via lubricant monitoring) can detect a potential failure up to six months beforehand, thermography between three-to-twelve weeks, and preventative maintenance only five-to-eight weeks. Furthermore, the failure becomes audible to the human ear around one-to-four weeks before and detectable as heat only one-to-five days (Bernet, 2011).

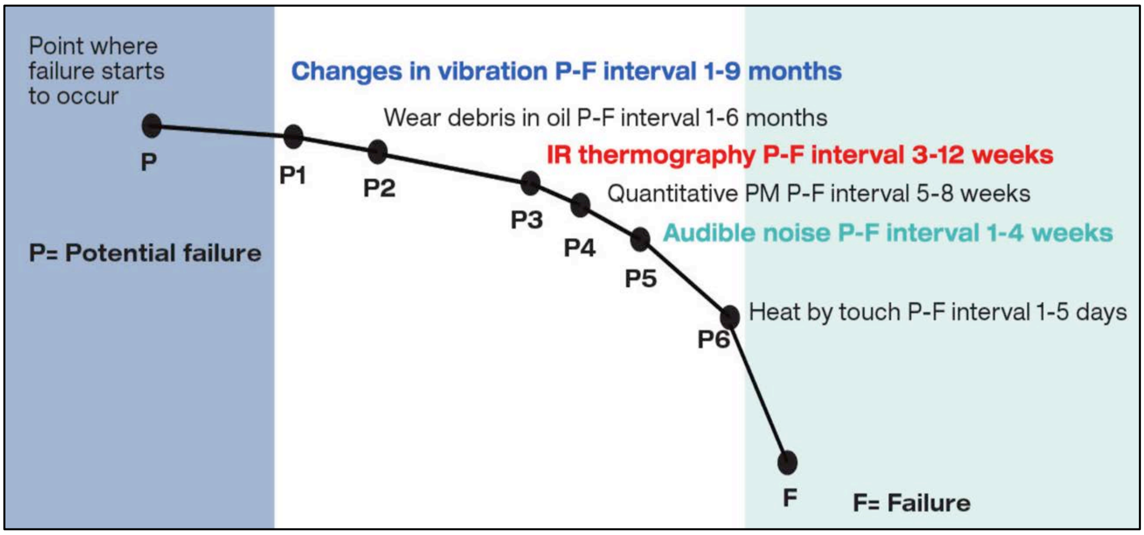


Figure 16: Potential failure curve over a nine-month period.

Source: (Bernet 2011)

3.5.1 OVERVIEW OF VIBRATION SIGNAL PROCESSING

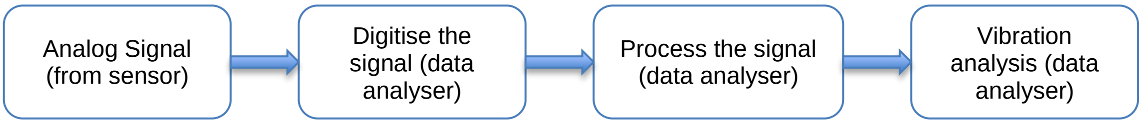


Figure 17: Vibration signal processing method

Source: Adapted from ISO 13773-2 (ISO, 2005)

As shown in Figure 17, the first step in acquiring vibration data is to capture the continuous analog signal. The sensors (also known as transducers) used for vibration monitoring all produce *"an analog electrical signal that is proportional to the instantaneous value of the vibratory acceleration, velocity or displacement"* (ISO 2005, p.1), consequently the corresponding analog signal is generated by powering the transducer via sending an electrical signal to it.

Secondly, to enable numerical processing and manipulation the captured analog signal has to be 'digitised'. This is achieved through the use of a analog-to-digital converter (ADC) which *"samples the analog signal and converts it to a series of numerical values"* (ISO 2005, p.2). The data analyser stores the numerical data in order to enable creation of time waveforms and the application of Fast Fourier Transform (FFT) to output a vibration spectrum. Accordingly, the two most significant parameters during this digitization are sampling rate and the resolution, therefore to ensure sampling validity and prevent aliasing, it is recommended to apply Nyquist Theorem i.e. sample at 2.56 times the maximum frequency of interest. Furthermore, to ensure reliability and sufficient data acquisition, it is best practice to capture numerous samples and implement averaging on the data (ISO, 2005).

Thirdly, the acquired numeric values are processed into useful information. This involves two common processing phases, first the time domain processing to generate time waveforms, and second the frequency domain method using the Fourier process (FFT) to create vibration spectrums and apply relevant filters. Additionally, the most prevalent quantity of measuring vibration over a given time period (e.g. root-mean-square (rms) values) is calculated to enable evaluations against international standards (ISO, 2005).

Lastly, vibration analysis is conducted on the processed information. The analysis is usually based on several comparisons such as against historic trends, international standards and/or in-depth Frequency Analysis of spectrums to identify known fault frequencies relevant to the asset in question (Berry 1997; ISO 2005). To aid the analysis process, it is important to capture key machine operating parameters such as the speed at which the machine is rotating/operating when data is acquired (ISO 2005).

3.5.2 COMMON VIBRATION FAULTS AND FREQUENCIES

As shown in Figures 18 and 19, some of the most common mechanical faults associated with CBM application (namely imbalance, misalignment, looseness and bearing faults) can be revealed through the analysis of vibration collected from axial, vertical and/or horizontal points (ISO, 2005, Watts, 2009; Bernet, 2011; Proviso-systems, n.d.). Each fault and associated frequencies are discussed below, also a summary of the fault frequencies is provided in Table 13.

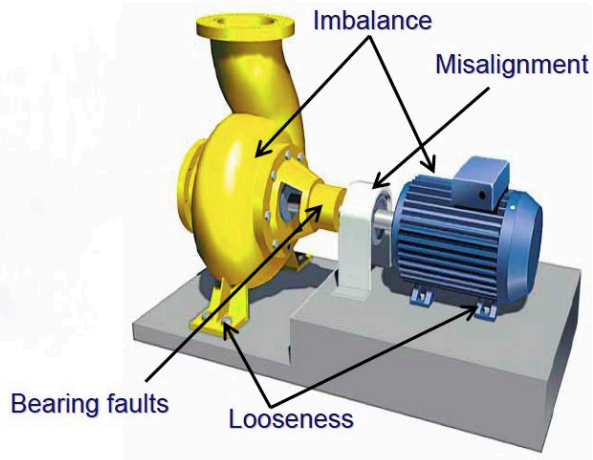


Figure 18: Illustration of fault locations on Pump and Motor
Source: ((Proviso-systems) n.d.)

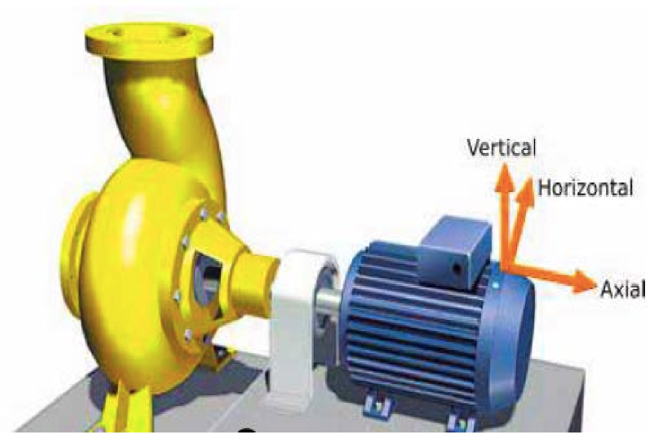


Figure 19: Illustration of measurement locations
Source: ((Proviso-systems) n.d.)

3.5.2.1 Unbalance

Unbalance (also known as imbalance) triggers premature failures, more specifically it is known to reduce bearing life and create excessive heat and vibration (Taneja 2013). A 'heavy spot' along the shaft, which consequently causes high vibration, instigates the occurrence of unbalance. The unbalanced rotating weight creates a centrifugal force, the cause of which can be a manufacturing defect or a maintenance issue. (Bernet, 2011; Kutin, 2009; Taneja, 2013).

Therefore, if the machine is out of balance, the resulting fault frequency is displayed on the vibration spectrum as a large peak at the running speed of the machine (i.e. a dominant peak at 1X - one times the machine running speed) (Berry 1997; ISO 2005).

3.5.2.2 Misalignment

Misalignment transpires when rotating axis of two shafts (e.g. pump and motor) are not aligned and/or at an angle due to improper installation or maintenance (Bernet, 2011; Kutin, 2009). Although a certain quantity of vibration is natural in any pump and motor, a misaligned pump causes excessive radial and/or axial vibration, which can instigate a large spectrum of faults including premature seal and bearing failure, increased motor speed and power usage, as well as greater operating temperatures. The consequence of such faults trigger not only higher operating and maintenance costs, but also reduce the lifespan of pump and motor. Therefore, the correct alignment of shafts is a key to success and must happen numerous times during the installation of a pump and checked periodically when operational, particularly as it is one of the main causes of vibration problems (Bernet, 2011; Kutin, 2009). According to a survey of 160 rotating machines randomly chosen for measurement, only 7% were aligned within acceptable limits (pruftechnik.com, 2013), highlighting the need for misalignment to be monitored as part of the maintenance schedule.

The dominant peaks at 1 and 2 times the machine running speed (1X and 2X) on the vibration spectrum is usually caused by misalignment (Berry, 1997; pruftechnik.com, 2013).

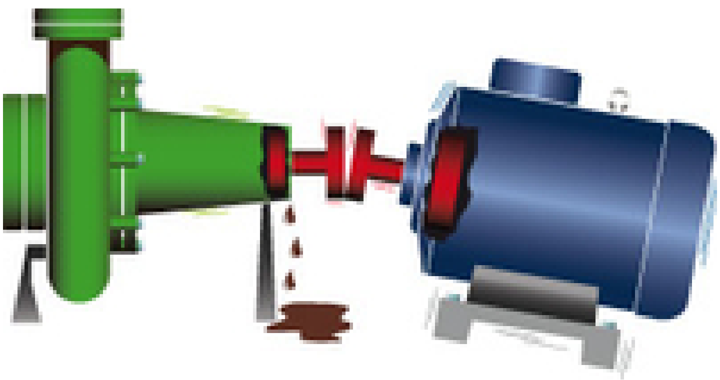


Figure 20: Illustration of pump and motor misalignment.
Source: (Pruftechnik 2013)

3.5.2.3 Looseness

Regular maintenance may ignore a pump and/or its motor that is loosely attached to mounts, however although this may or may not be the cause of the vibration, it can increase the natural vibration thus contributing to performance and efficiency degradation as well as bearing damage (Bernet, 2011; Kutin, 2009).

A vibration spectrum will show looseness as dominant peaks 3 to 8 times the running speed of a machine (3X to 8X) (Berry, 1997; pruftechnik.com, 2013).

3.5.2.4 Bearing Faults

Bearings are the most common components in rotating machinery and play a significant role in the correct operation, efficiency, reliability and safety of the machinery. However, the limited life of bearings can be greatly influenced by installation, operating condition and maintenance of the machinery (Kutin, 2009; Jammu and Kankar, 2011).

According to Bachus and Custodio (2003), pumps and motors can get inundated with unforeseen premature bearing failures and although the cost of the bearing itself is small, the related costs (direct and indirect) of repairing an unexpected failure can be substantial:

> *"…a pump bearing may only cost $20.00 to buy, but its failure could also take out a mechanical seal. Now, besides the cost of the bearing and mechanical seal, is the cost of disassembly and reassembly of the pump. And there will be other replacement parts to change although they may or may not have failed. Some of these would be the casing gaskets, pipe flange gaskets, set screws, snap rings, clip rings, wear bands, shims, oil seals, nuts and bolts, not to mention the oil or grease lost. Then there is the time dedicated to the repair, which is also the time lost from production."*

(Bachus & Custodio 2003, p.160)

The most common causes of bearing failures are consequent of a lack of appropriate maintenance and/or abnormal operating conditions, rather than the myth that the bearing or lubricant itself triggers the failure (Jammu and Kankar, 2011; Mobil, N.D). Therefore, the importance of bearing maintenance emphasised by the extensive and mostly successful research undertaken in the last decades, is exploiting the use of numerous techniques, most prominently vibration analysis (Hoflin 2009; Jammu & Kankar 2011).

A defective bearing produces vibration frequencies that are not exact multiples of the running speed (1X), i.e. they are non-synchronous (such as 0.3X). A defect can be further investigated, for example the complex and extensive research on bearing defects provides four key 'forcing frequencies' namely, ball pass inner race (BPI), ball pass outer race (BPO), fundamental train (FT) and ball spin (BS). Cross-examining the non-synchronous frequencies against the bearing manufactures forcing frequencies can precisely isolate the defect location (Berry, 1997; ISO, 2005; pruftechnik.com, 2013).

#	Frequency Bands	Frequency Range	Units	Explanation / Faults detection
1	Overall Velocity	0.15 - 80xRPM	mm/sec	General Vibration Severity
2	1xRPM	0.15 - 1.5xRPM	mm/sec	Unbalance
3	2xRPM	1.5 - 2.5xRPM	mm/sec	Misalignment / Twice Electrical Frequency
4	3-8XRPM	2.5 - 8.5xRPM	mm/sec	Looseness Harmonics / Blade/ Vane Pass Range
5	9-35xRPM	9.5 - 35.5xRPM	mm/sec	Mid Velocity Range Bearing Frequency harmonics / Cavitation
6	36-80xRPM	35.5 - 80xRPM	mm/sec	High Velocity Range Bearing Frequency harmonics / Cavitation / common motor slot / rotor bar Frequencies
7	HFD (High Frequency Detection)	1kHz to 20kHz Or 5kHz to 20kHz	G's	Early detection of high frequency energy, such from inadequate lubrication, early/mid/late stage bearing defects.
8	Waveform Pk-Pk	N/A	G's	Mid to late stage impact related fault detection such as bearing faults and rotating looseness faults
9	Crest Factor	N/A	(unitless)	Spikiness of signal (ratio of Pk / RMS) which is used to detect things such as sharp impacts from bearing elements including cage, transient events
10	Overall PeakVue	1kHz High Pass Filter passes all frequencies below this and measures high frequencies from 1kHz to full response range of the accelerometer (PeakVue upper response range is 80kHz and it samples at over 104,500 samples/ per second)	G’s	See below, but not as sensitive as the PeakVue Waveform Pk-Pk
11	PeakVue Waveform Pk-Pk	N/A	G's	Pk to Pk of PeakVue time waveform which is extremely sensitivity (often can be 10x higher than the amplitude of the overall PeakVue overall value) useful for detection of high frequency stress / shock wave detection from lack of lubrication, increased friction between rolling element due to increased loading, very early detection of bearing defects developing beneath the surface of the bearing and of course mid/late stage failure.

Table 13: Common frequency bands, ranges and explanations used in academia and industry.

Source: Adapted from various e.g. (Berry 1997; ISO 2005; Pruftechnik 2013)

3.5.3 <u>VIBRATION ISO STANDARDS</u>

In addition to analyzing the vibrations via fault frequencies, it is possible to compare the overall velocity root-mean square (rms) to established international standards. The ISO Standard 10816 (technical revision of ISO 2372 and ISO 3945) is commonly utilised to evaluate the vibration severity measurements and provides an indication of the machine condition. The Standard includes 7 parts and is broadly titled as '*Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts'* (ISO 10816, 2009).

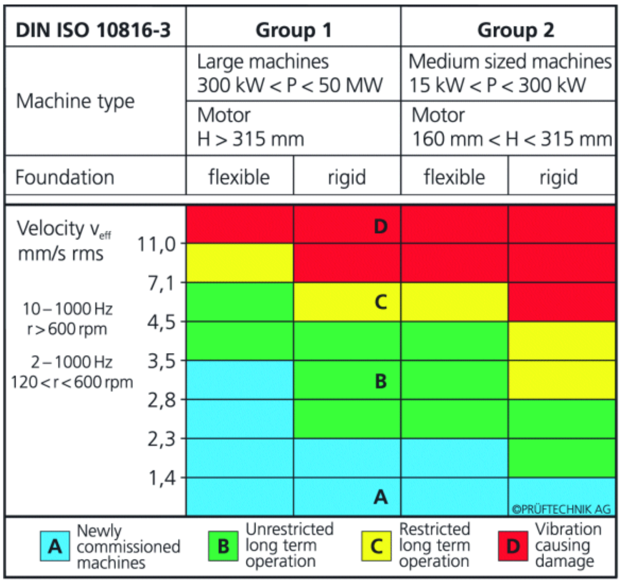


Figure 21: ISO 10816-3: Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15 000 r/min when measured in situ.

Source: ISO 10816 (2009)

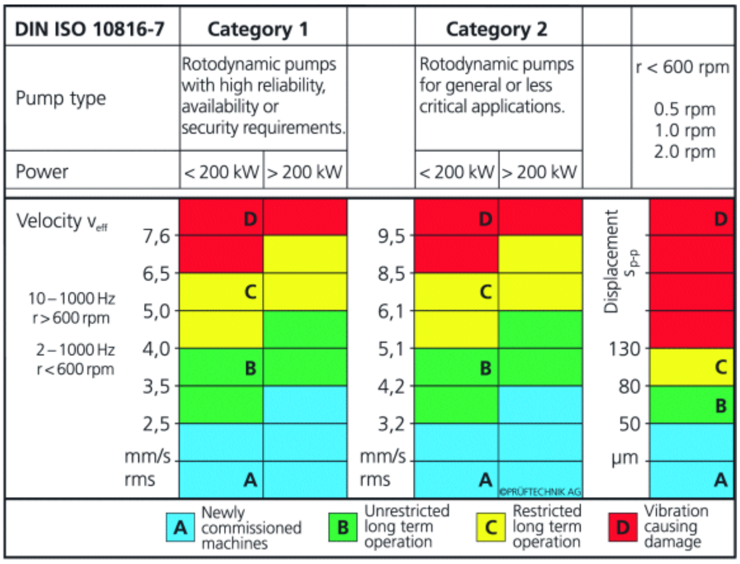


Figure 22: Rotodynamic pumps for industrial applications, including measurements on rotating shafts.

Source: ISO 10816 (2009)

ISO 10816 part 7 has been a recent addition, valid since August 2009 it plays a significant role in the evaluation of vibration severity readings collected from centrifugal pumps (ISO 10816, 2009; Pump-zone, 2012). These internationally recognised evaluation standards clearly shows the extent to which research in this field is widespread and established. Furthermore, the standards can be interpreted into maintenance activities as shown in Figure 23.

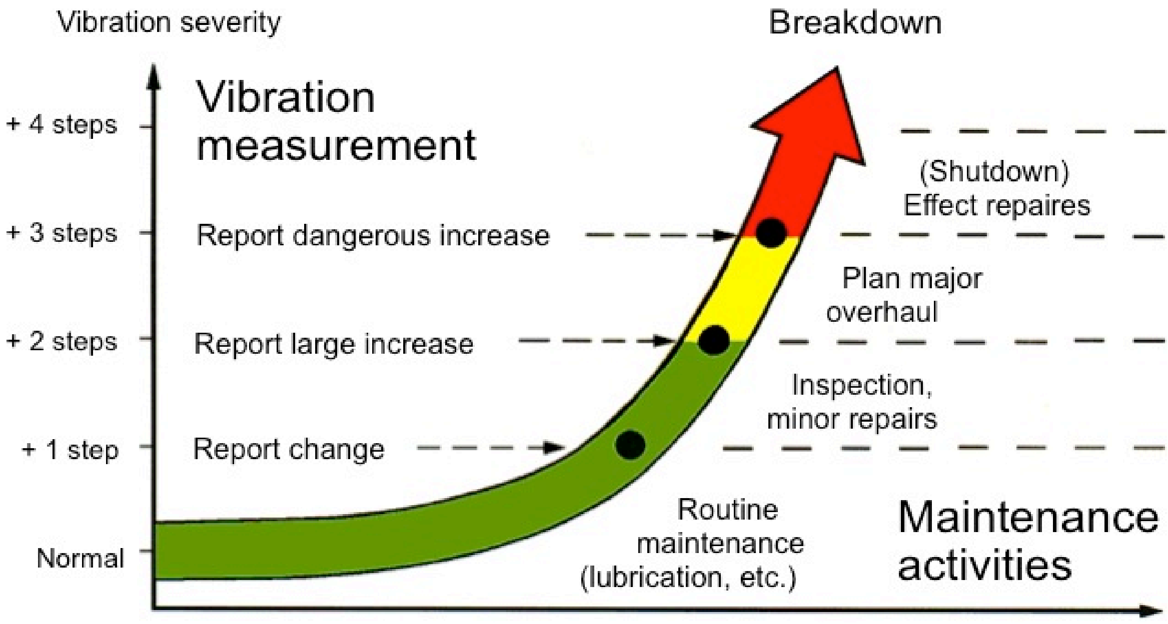


Figure 23: Interpreting ISO standards in the context of maintenance activity
Source: (Pruftechnik 2013)

3.5.4 SHOCK PULSE METHOD (SPM)

For the detection of bearing defects, an alternative to vibration monitoring is Shock Pulse Method (SPM). Originating from Sweden, the SPM technique has been utilised in various applications since Eivind Sohoel patent in 1969, currently it is a generally accepted as a suitable quantifiable approach for identifying bearing deterioration and lubrication condition (Zhen et al. 2008; Hoflin 2009; Sundstrom 2010).

The technique is based on the physics foundation that shock pulses are generated in the interaction between the 'raceways' and 'rolling elements' of rolling element bearings consequently by calculating the 'maximum normalised shock value' through considering bearing diameter and revolutions per minute (RPM), the bearing condition can be established (Hoflin, 2009; Sundström, 2010). Using this principle, SPM removes the requirement for complicated data analysis and provides a single value indicating the condition of the bearing (Hoflin, 2009; Sundström, 2010), which is the fundamental benefit. Additionally, the interpretation of the shock pulse through a normalised scale allows the condition to be directly evaluated as it is presented as green, yellow and red (IPE, 2009; Sundström, 2010).

Although SPM and other techniques such as temperature, ultrasonic noise and acoustic can all be used to monitor bearing condition, vibration analysis is the most common method (Sundström, 2010; Ahmad and Kamaruddin, 2012). However, the primary weakness of vibration analysis is that it can be influenced by outside factors such as machine size and background noise and vibrations, consequently by time the fault is detectable, the bearing can *'reach an advanced stage of damage'* ((SPM), 2002); IPE, 2009; Sundström, 2010). In contrast, the SPM technique is not influenced by such external factors since it utilises a specialised transducer (piezo-electric accelerometer that is mechanically and electrically tuned) (Sundström, 2010). Zhen et al., (2008, page 1) highlight that *"direct demodulation may mistakenly estimate the shock value in the SPM"* therefore to compensate it may be more effective to use a new approach that is based on wavelet transform lifting scheme, however the research could not find sufficient to support for this claim.

Although SPM has been documented to identify bearing defects earlier than vibration analysis ((SPM) 2002), as a patented technology, the application of SPM specifically for bearing defect condition monitoring is usually considered an expensive option hence reserved for high-value, critical rotating assets such as large compressors, wind turbines and machinery relating to oil/gas (Mitchell & Capistrano 2007; Amin & Pitt 2014), for example IPE (2009, p.1) highlights that through the use of online SPM technology, Centrica has *"savings in excess of £10m over seven years"* from efficient asset energy savings and removing the need to store spare parts.

3.6 APPLICATION AREAS OF CBM

There are several examples of CBM application case studies presented in the literature, this section details the most recently presented with a focus on industries

Recently, Shin & Jun (2015) undertook four case studies (as described in Table 14) in order to stress, *"CBM is not always effective in all cases"* (p.125) and CBM may be more suitable for high valued products or large-scale plant industries. More specifically, due to mass consumption products, CBM may not be a cost effective maintenance solution in automotive industry, and since the economic benefits will vary based on product and lifecycle, detailed analysis is needed in prior to implementation to establish the importance of maintenance operations and overall maintenance strategy.

Furthermore, based on the findings, they highlight that increasing number of industries will endeavour to adopt CBM inline with Information Communication Technology (ICT) drivers, however it should be stressed that "*CBM is not just a box you can buy to integrate onto your platform or system, but is a set of integrated technologies, processes, and capabilities that together enable CBM to be realised" (p.126).*

Case study	**Description**
Oil analysis: Estimating the change time of engine oil on a vehicle (truck).	Developed a predictive algorithm that analysed degradation status with mission profile data in order to establish suitable changing time of engine oil.
Crack propagation analysis: Vehicle lift arm structure (Track Type Loader – TTL).	Estimating the remaining useful life (RUL) of the lift arm structure based on degradation state data, mission profile data and future usage.
Event data analysis: applying CBM based on analysis of usage data.	Usage data of a locomotive is correlated using an Artificial Neural Network (ANN) to acquire product status.
Vibration analysis: estimating failure time of a compressor.	Used magnitude of vibration (peak-to-peak) obtained from the relative shaft to propose a prognosis algorithm using Markov Model Theory.

Table 14: Case studies by Shin & Jun (2015)

Source: Shin & Jun (2015)

Similarly, Prajapati et al. (2012) demonstrated the wide variety of CBM application areas, including *“manufacturing, process industry, military, naval, air forces ground vehicles, IT infrastructure, commercial vehicles and aviation/aircraft”* (p. 394). Moreover, they consider diagnostics, prognostics, data mining and artificial intelligence to be enablers of CBM; consequently predict that the popularity of CBM research in such a wide spectrum of industries will reduce unnecessary maintenance thus wasting of time and money.

3.6.1 MILITARY AND AVIATION

As pioneers of CBM, the U.S. Army is implementing a variety of CBM programmes under its broad ‘CBM+’ initiative (Prajapati et al., 2012). For example (as demonstrated by Patrick et al., (2009)), to enable transition from time-based maintenance to CBM thus improve health monitoring and fault predictions relating to helicopter component failures, they are deploying Health and Usage Monitoring Systems (HUMS). HUMS is an alternative method to estimate the condition of a system. It is centered on the correlation between certain usage profiles (record of helicopter operating parameters) and the resulting system degradation (Patrick et al., 2009; Tinga, 2010).

HUMS is a good example of a successful condition monitoring method currently being investigated in practice, the capability of which has been widely demonstrated with rotorcraft components for effective fault detection before they failure (Patrick et al., 2009; Tinga, 2010). Moreover, Patrick et al., (2009) demonstrate the practicality and viability of enhanced diagnostics (based on numerous sources of data) to assist prognostics when applying CBM (instead of time-based maintenance) on a drive train bearing of Sikorsky H-60 helicopters.

3.6.2 WIND POWER INDUSTRY

Recently, the international drive towards renewable energy sources and subsequent configurations of large-scale Wind Energy Conversion Systems (WECS) (i.e. wind farms) is presenting the responsible maintenance managers with new challenges. For example, logistical constraints relating to the application of time-based maintenance, and more specifically, the transportation of large components (e.g. cranes, ships and/or helicopters for access). As a result of such challenges and a natural motivation to reduce the cost associated with maintenance, the application of CBM through online condition based monitoring systems that allow integrated fault detection relating to mechanical and electrical faults associating with key component failures, is becoming increasing evident in this industry (Amirat et al., 2009; Børresen, 2011).

Researchers such as (Børresen 2011; Hoflin 2009; Amirat et al. 2009) have demonstrated the practicality, viability and potential of CBM through numerous studies that enable early fault detection and diagnosis relating to WECS components such as blades, drive trains, generators, gearboxes and rotors. Consequently, the technologies and research relating to CBM are being deployed by the wind turbine manufacturers to incorporate the relevant sensors and systems into the design and construction, which enables them to present clients with a long-term online CBM service package.

3.6.3 PROCESS AND MANUFACTURING INDUSTRY

The paper presented by Veldman et al., (2011a) focused on Process industry described as manufacturers which create products through the process of *'mixing, separating, forming and/or chemical reactions'* (p.47). The assets in this specific industry include rotating equipment (e.g. pumps), electrical systems and static assets such as complicated piping networks, vessels and heat exchangers. The boundaries within which these assets operate (to generate the products) are continually under stringent quality control measurements. The maintainable assets function to provide overall control and manipulation of parameters such as flow rates, temperatures, pressures, and states of solids, liquids and gases.

They developed and examined eight assumptions ('postulates') found in CBM literature towards the aim of exploratory theory building. Structured interviews at five case companies (summarised in Table 15) were followed up with telephone interviews. Participants included managers (maintenance) and engineers (process and maintenance). Furthermore, 'presentation material' and 'written documents' were supplemented as an additional data source.

They found only two (out of the eight) postulates to be fully supported, firstly relating to technical systems that companies make use of third parties for CBM tasks and secondly relating to managerial systems that 'process companies create autonomous organisational units in which the actual CBM tasks take place'. Similarly, there were two postulates that were 'not supported'. Both of these relate to 'managerial systems' suggesting that companies do not 'use strict procedures to execute CBM' and companies do not 'make use of employee training for correct execution of CBM'.
Additionally, they found 'limited support' for the other fifty per cent of the postulates. These postulates were in relation to 'technical systems' and 'workforce knowledge'. Firstly, with regards to limited support for technical systems it was in relation to the use of 'more diagnosis than prognosis' and the 'use of information systems and specialised software'. Secondly, the limited support in respect of workforce knowledge suggested an inadequate availability of 'sufficient domain related knowledge' within companies using CBM. Finally, they found that 'domain related types of workforce knowledge' is only critical for the success of diagnosis not prognosis.

The plants and equipment vary in characteristics, redundancy and ages; consequently such factors were scoped out of the research considerations. Furthermore the 'physical production technologies' are only relatable across the companies at a 'general level'. It is important to highlight that the researchers specifically state their intent to evaded 'testing' of the postulates since the assumptions lacked explanatory assertions. Nevertheless, this study demonstrates that CBM in the form of detection and diagnosis is being applied in this industry through speciality third parties. Moreover, there are autonomous units fulfilling the function of CBM. However, further emphasis is required on employee training and procedures to execute CBM programmes.

Postulate *[category]*	**Result overview**
1. Process companies apply more diagnosis than prognosis in their condition-based maintenance program. *[Technical Systems]*	Limited Support
2. Process companies make extensive use of information systems and specialised software in their condition-based maintenance program Process. *[Technical Systems]*	Limited Support
3. Process companies make use of third parties for specialised condition-based maintenance tasks. *[Technical Systems]*	Supported
4. Process companies create autonomous organizational units in which the actual condition- based maintenance tasks take place. *[Managerial Systems]*	Supported
5. Process companies make use of strict procedures to execute their condition-based maintenance program. *[Managerial Systems]*	Not Supported
6. Process companies make use of employee training for the correct execution of condition-based maintenance program. *[Managerial Systems]*	Not Supported
7. Process companies make sure sufficient domain related knowledge is available for their condition-based maintenance program. *[Workforce knowledge]*	Limited Support
8. The integration of the domain-related types of workforce knowledge is critical for the success of diagnosis and prognosis tasks. *[Workforce knowledge]*	Supported for diagnosis

Table 15: Summary of postulate findings in Process Industry

Source: Veldman et. al., (2011a)

3.6.4 PHARMACEUTICAL INDUSTRY

Rajan and Roylance (2000) investigated plant machinery in the pharmaceutical industry and developed a mathematical model to predict the cost effectiveness of maintenance strategies for pumps, fans and gear transmissions. The key finding put forward include firstly, that machine reliability data is needed in order to establish cost effectiveness of different strategies, secondly breakdown maintenance is only slightly more costly than planned maintenance. Although, per pump, the breakdown costs were 1.8 times greater than planned maintenance cost, an increase in pump reliability will make breakdown maintenance more efficient than planned. Lastly, and most significantly, overall the most cost effective pump maintenance strategy is CBM using vibration analysis, while breakdown maintenance is the least cost effective, planned maintenance appears marginally close in the middle. Over a five-year period, the average saving from using vibration measurements to trigger maintenance against a time-based system was £224.80 per annum per pump. Although this is based on pump data period from 1990 and a vibration meter costing £1170, it demonstrates practicality and potential for financial savings.

3.6.5 BUILT ENVIRONMENT

Fault detection and diagnosis (FDD) of building heating, ventilation and air condition (HVAC) assets have been researched actively for over a decade, consequently there is an extensive amount of research specifically relating to understanding common faults based on performance and data analysis (Katipamula & Brambley 2005). A comprehensive example is the research conducted specifically on Chillers (see Comstock et al. 1999; Comstock & Braun 1999; Xiao et al. 2011).

Whilst various studies have demonstrated the potential of data driven FDD on individual HVAC systems and sub-systems (such as air handling unit fans, pumps, chillers, cooling and heating coils etc.), overall the research in relation to buildings maintenance management is incoherent and deprived of innovations such as CBM (RICS 2009; Noor & Pitt 2009a). Moreover, the definitive reference for maintenance managers and building service engineers in this domain, CIBSE Guide M (CIBSE 2008), appears to provide limited detail by suggesting that CBM techniques are applied when assets are expensive to maintain/replace, or when the failure leads to higher costs and unacceptable situations (i.e. health and safety).

Furthermore, the lack of comprehensive and integrated management research that focuses on the application of CBM (to enable transition from the prevailing time-based maintenance policies) is apparent in the survey of literature (Amin & Pitt 2014; Amin et al. 2015).

For example, Buswell et al., (2003) demonstrate the wealth of performance and operations data accessible though a modern building management systems (BMS) to enable the application of fault detection and diagnosis modelling on individual sub-systems such as air-handling unit cooling coils. However, data relating to only one particular sub-system is analysed from the technical practicality perspective by Buswell et al. (2003) without much consideration towards management or operations.

Similarly, Hegazy et al., (2010) acquired reactive maintenance data for eighty-eight schools to develop an asset management condition prediction method that reduces unnecessary reactive maintenance and informs inspection planning. The detailed analysis of reactive data focused on two key components namely, the number of reactive maintenance work orders and the cost associated with the works. Based on this analysis a prioritisation mechanism could be implemented, however the analysis is limited to only two parameters thus prediction accuracy is significantly impacted in the event no prior reactive maintenance has been required on assets (which is common for building assets).

More recently, Poór et al., (2014) provide a succinct literature overview of building maintenance objectives, strategies and potential benefits in relation to energy management, emergency preparedness and health and safety. However, they do not present any primary research to support the brief summaries.

Such incomprehensive, incoherent and limited sample of literatures demonstrate the ‘no mans land’ gap of CBM research in the built environment when compared to other industries (i.e. aviation and processing). This is further reinforced by the fact that this literature survey was unable to identify any robust application focused research, or specific guidance for application within the built environment (the only three relevant research studies identified have been discussed above).

Therefore, taking into consideration the longstanding history, documented advantages and the robust execution process associated with the application of CBM, it is necessary to empirically investigate and demonstrate the potential impacts of implementing CBM technologies (such as vibration analysis) within the built environment and more specifically, buildings maintenance management (based on evidence and guidance that is transferable from international standards and other industries).

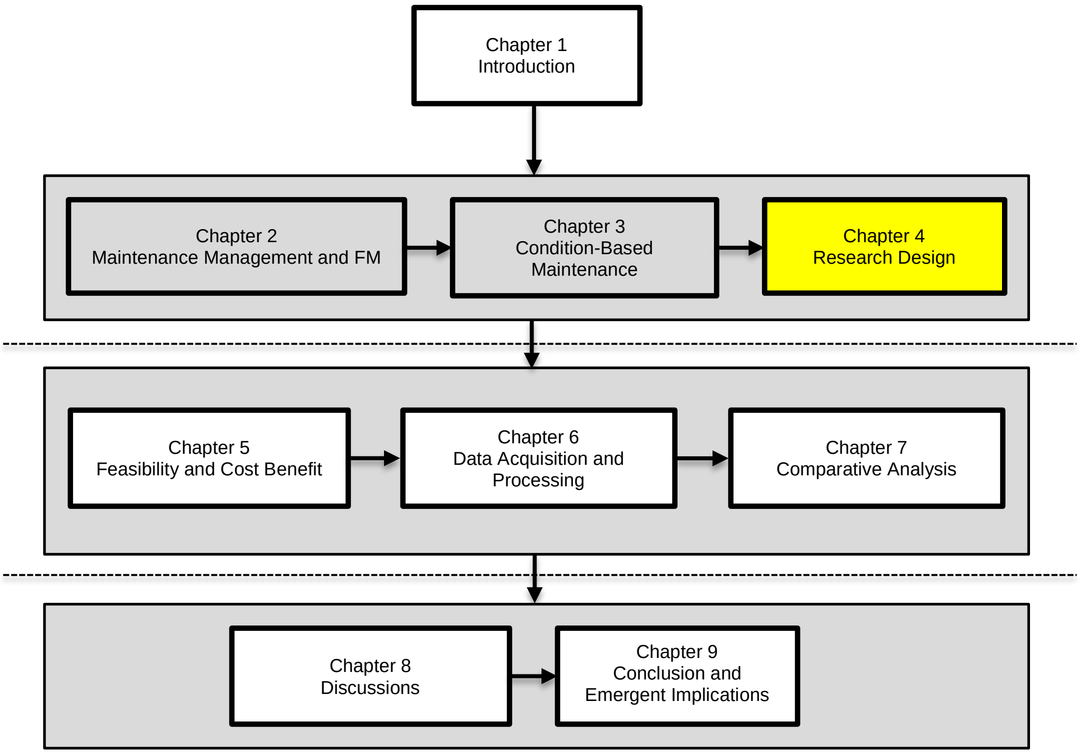
3.7 BOX 3: SUMMARY OF CONDITION-BASED MAINTENANCE

This chapter provides a detailed review of CBM literature relevant to this study, in summary:

- CBM has been around since the 1940s and was first instigated by the Rio Grande Railway Company and subsequently adopted by the U.S Military.
- Commonly referred to as Predictive Maintenance, the goal of CBM is to inform maintenance management decision-making.
- Prior to the 1970s, CBM was reserved for a small, distinct minority of high-risk and high-value assets such as automotive and aerospace. However, accelerated by the advancements of ICT, the application of CBM techniques can nowadays be attributed to a higher number of large organisations and diverse industries.
- There are numerous advantages documented with CBM applications, these can be categorised into two groups namely, its superiority over other maintenance policies and beneficial impacts to the service delivery and operations.
- Several disadvantages are also discussed in the literature. The most popularly deliberated is the high investment costs that are necessary and challenging to justify. Another aspect of limitation is that research rarely includes management and operational support requirements, nor does it document the successful integration into existing business systems and processes. As a result, the actual benefits are rarely achieved in practice.
- Therefore, the existing body of knowledge associated with CBM is generally based on technical experimental condition case studies, which can be broadly categorised into three groups: technical, computer and information science, and mathematical model and decision-making. Such constraints further contribute to the empirical management research gaps, for example relating to the practical application interpretations, knowledge, and understanding of the complex data and technologies discussed by literatures.
- Literature surrounding the execution process also appears to be incomplete. However, wealth of international standards can be referenced to adequately fill this gap.
- The most relevant international standard provides twenty-seven different condition monitoring and machine performance considerations. However, the most robust and frequently applied technique is vibration analysis, which is widely discussed and has an abundance of processing and fault documentations that can be transferred to machines within the buildings.
- Literature relating to the actual applications of CBM is limited to certain industries, and there appears to be a significant gap in empirical research relating to the built environments building maintenance management.

The next chapter will detail the research design for this study.

4 RESEARCH DESIGN



This chapter firstly outlines the main areas of interrogation of this research. Secondly, following the examination of numerous approaches for conducting research, an action research approach using a case study based research design is adopted employing a multi-strand mixed method data collection instrumentations (qualitative and quantitative). Thirdly, details are provided of the selected case and assets. Lastly, the data analysis procedures and research quality and validity are discussed.

4.1 AREAS OF INTERROGATION

Following an extensive review of literature in the field of maintenance management to provide an in-depth analysis of the underlying context (Chapter 2), and CBM techniques with cases of industry application (Chapter 3), it has been established that:

- The young, dynamic and complex domain of 'maintenance management' is a core competence of FM.
- Whilst other industries have embraced third-generation 'predictive' maintenance concepts (i.e. RCM and customised), the built environment and FM continues to lag behind with the continuous application of second-generation lifecycle and time-driven maintenance philosophies.
- Other industries (aviation, manufacturing) that have similar assets to FM have demonstrated the effectiveness of applying CBM tools and technologies (especially, vibration analysis).

Therefore, the focal point of this study is the application of condition-based maintenance philosophies using condition monitoring and statistical data analysis within the context of FM building maintenance and operations. Accordingly, in the process of implementing a new maintenance concept proposal (see Figure 30), this study aims to answer the following question: What are the impacts of implementing Condition-based maintenance policies in a buildings maintenance context?

4.2 THE RESEARCH PHILOSOPHY

The traditional long-standing epistemological debate relating to philosophical approaches of undertaking research is ultimately based on two paradigms, namely positivism and realism (Bryman 1984; Amaratunga & Baldry 2001; Sale et al. 2002; Amaratunga et al. 2002; Saunders et al. 2009). Table 16 summarises the characteristics of both schools of thoughts.

Although some literature appears to contradict the principle characteristics of the paradigms, for example, in Amaratunga & Baldry (2001, p.96) it is highlighted that the positivist paradigm is *'often designated as qualitative research',* yet in Amaratunga et al. (2002, p.18) it is stated that *'positivism uses quantitative and experimental methods to test hypothetical-deductive generalisations'.*

Theme	Positivist Paradigm	Realism Paradigm
Approach	Quantitative	Qualitative
Ontological Position	There is only one truth.	There are multiple realities or truths depending on the one's construction of reality.
Basic beliefs	The world is external and objective. Observer is independent. Science is characterised by empirical research.	The world is socially constructed and subjective. Observer is part of what is observed. Science is driven by human interest.
Research should	Focus on facts. Look for causality and fundamental laws. Formulate hypotheses and test them. Reduce phenomena to simplest elements.	Focus on meaning. Try to understand what is happening. Look at the totality of each situation. Develop ideas through induction from data.
Preferred method in the research	Operationalizing concepts so they can be measured. Taking larger samples	Using multiple methods to establish different views of the phenomena. Small samples investigated in depth.

Table 16: Key characteristics of positivist and realism paradigm
Source: adapted from (Bryman 1984; Amaratunga et al. 2002; Sale et al. 2002; Saunders et al. 2009)

Majority appear to be in agreement that positivism is a quantitative paradigm based on the ontological foundation that 'there is only one truth'. Similar understanding is available for the contrasting realism paradigm (also referred to as interpretivism or constructivism), which is qualitative and ontologically has multiple truths depending on the researchers construction of reality (Bryman 1984; Amaratunga et al. 2002; Sale et al. 2002; Saunders et al. 2009).

Therefore, the foundation of the positivist paradigm is empiricism with a mixture of deductive logic and mainly quantitative methods, which are considered to achieve highly structured methodologies (where the researcher is independent), and quantifiable outcomes (with hypotheses formulated and tested). In contrast, the realist paradigm is based on the notion of inductively understanding the social forces and procedures with the assumption that the researcher is part of the social world being researched (Saunders et al. 2009; Amaratunga & Baldry 2001; Amaratunga et al. 2002; Sale et al. 2002).

Nevertheless, both paradigms do share philosophical qualities for example, they both attempt to understand the world and/or society in which we live (Bryman 1984; Sale et al. 2002; Saunders et al. 2009). Consequently, there is significant support for conducting research using a combination of both qualitative and quantitative methods, not only to eradicate weaknesses associated with individual approaches but also to provide superior methodological strategy and better quality of outputs (Cameron 2011; Amaratunga et al. 2002; Creswell 2003; Hall 2013; Teddlie & Tashakkori 2006; Johnson et al. 2014).

Therefore, the core research philosophy undertaken in this thesis is a positivist epistemological position. However, the research also has elements of realist philosophy. Fundamentally, a mixed methods research framework is implemented in this study.

4.3 ACTION RESEARCH PLATFORM

According to Alexander et al. (2004), since the nature of FM is fundamentally practical, research and practice are synergistic. Therefore, majority of research in FM is traditionally undertaken through an action research approach which endeavours to essentially bridge the gap between research and practice (Somekh 1995; Hall & Coats 2005; Hall 2013). Action research is a unique form of enquiry described as *"any research into practice undertaken by those involved in that practice, with an aim to change and improve it" (Hall & Coats 2005, p.4).* Similarly, Altrichter et al. (2002, p.125) recognise the capabilities of action research in relation to practical depth and discourse of theory, they provide the following detailed definition:

> *"A form of collective, self-reflective inquiry that participants in social situations undertake to improve: (1) The rationality and justice of their own social or educational practices; (2) The participants' understanding of these practices and the situations in which they carry out these practices. Groups of participants can be teachers, students, parents, workplace colleagues, social activists or any other community members – that is, any group with a shared concern and the motivation and will to address their shared concern. The approach is action research only when it is collaborative and achieved through the critically examined action of individual group members."*

An effective vehicle for such collaborative research strategy implementation is the use of case studies involving data collection, observations, interviews through researcher participation with end users and the management of the organisation within which the study is based (Alexander et al. 2004; Hall 2013; Hall & Coats 2005). However, others suggest action research can occur in any situation which meet the condition detailed in Table 17.

A situation in which:

- People reflect on and improve (or develop) their own work and their own situations
- By tightly inter-linking their reflection and action; and
- Also making their experience public not only to other participants but also to other persons interested in and concerned about the work and the situation.

And a situation in which there is increasingly:

- Data-gathering by participants themselves (or with the help of others) in relation to their own questions;
- Participation (in problem-posing and in answering question) in decision-making;
- Power-sharing and the relative suspension of hierarchical ways of working towards industrial democracy;
- Collaboration among members of the group as a 'critical community';
- Self-reflection, self-evaluation and self-management by autonomous and responsible persons and groups;
- Leaning progressively (and publicly) by doing and making mistakes in a 'self-reflective spiral' of planning, acting, observing, reflecting, re-planning, etc.
- Reflection which supports the idea of the '(self)-reflective practitioner'

Table 17: Core elements of action research definition and situation
Source: (Altrichter et al. 2002)

Accordingly, this study was conducted through a four year Engineering doctorate (EngD) partnership between the research institution (University College London) and an organisation (Skanska). The key characteristics of this collaborative approach include:

- The researcher was employed at the research site on a full-time basis (as a *'Research Engineer')* throughout the duration with accountability and responsibilities to deliver the research aim in-line with the research strategy defined and agreed within a research Project Definition.
- Weekly meetings with research supervisors.
- Monthly research board meetings, which included research supervisors (Professors) and senior management (Senior Managers and Directors), as well as other doctorate researcher undertaking research projects.
- Researcher had the ability to be part of the end user team, as well as directly engage with all levels of organizational influence (strategic, tactical and operational). Thus enabling a comprehensive understanding of reality.

This collaborative and iterative research and practical development approach, with continuously practical improvement and action through collective reflection and intellectual inquiry, provided the underlying research platform (as demonstrated by Figure 24) (Altrichter et al. 2002).

This model reflects the continual management supervision and input from the various meetings related to the project.

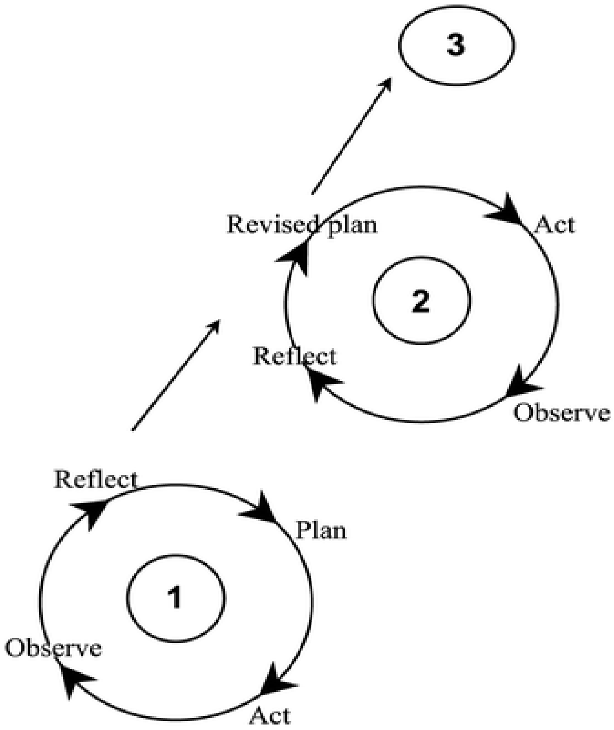


Figure 24: The spiral of action research cycle
Source: (Altrichter et al. 2002)

4.4 RESEARCH APPROACH: MIXED METHOD

Creswell (2003) describes the framework for research design as a process where the various components of inquiry (conceptulised by the researcher) interrelate to produce the research approach. Moreover, the practical implementation of the synthesised research approach is undertaken using research instruments. However, as stressed by Brannen (2005), prior to the pragmatic selection and subsequent application of the research approach and accompanying instrumentation, it is important to contemplate the nature of the research problems. Therefore, the main justification for the selection of the research design considered the following three aspects:

1. Domain of the study: The research investigation was based in the area of the built environment. The definitive goal of research in the built environment is to embrace the multi-disciplinary requirements in relation to the specific context of research domain and add value to the body of accumulated knowledge. Therefore, research undertaken in the built environment has a tendency of being either qualitative or quantitative, and usually there is a preference towards the latter than the former (Amaratunga & Baldry 2001; Amaratunga et al. 2002).

Amaratunga et al (2002) discuss the merits and detriments of both methodologies. For example, as a positivist theme, the quantitative paradigm can utilise statistics and data aggregation, yet the methods can be considered as rigid and synthetic. In contrast, the qualitative paradigm based on phenomenological arguments can use natural data collection methods but interpreting the data is far more challenging consequently results can have lower credibility than quantitative approaches (Amaratunga et al., 2002). They suggest the use of a mixed method approach (i.e. combining qualitative and quantitative) as an alternative could not only offset weaknesses of applying a single methodology, but also enrich the research conducted within the built environment.

2. The research objectives: The objectives of the research (see Section 1.4.2) indicate the analysis requirement would involve collection, amalgamation and aggregation of various data types from numerous sources (e.g. raw data from assets, systems and interviews with end users), consequently data collection will need to include various research instruments.

3. Nature of the research subject: The research aims to investigate the transfer and embedding of techniques that are essentially untested within this specific field. Consequently little initial information concerning industry application is available. Additionally, in order to establish the effectiveness of such techniques, the research required a potentially significant amount of investment justification that can only be undertaken with a comprehensive understanding of reality with close partnership with end users, and considered for approval at the strategic level of an organisation. Finally, the complex and dynamic multi-disciplinary nature of the research context also presented challenges in ensuring generalisability. As a result, the selection of research approach and design had to ensure the relevance of the study to these significant challenges.

These three research design justification elements were combined with the literature survey, Table 18 highlights the research approaches that were identified and considered during an extensive review of literature in area of research epistemology.

To address the mentioned challenges, especially the close engagement and partnership with end users, and the dynamic and complex context, the approach selected was based on the following factors:

- An action research approach that employed the practical problem centred and real world oriented research philosophy explained by Creswell (2003). This ensured that the research investigation was synergistic and bridged the gap between research and practice, as described by Alexander et al. (2004).
- The built environment research has a reputation of principally dominated by quantitative research, yet as suggested by Amaratunga et al., (2002) a more desirable approach would be a mixed method framework, where quantitative and qualitative techniques amalgamate to contribute to the overall depth of the same study (Azorín & Cameron 2010).
- An iterative refinement approach was utilised based on the 'Action Research Cycle' (Kemmis 2009; Altrichter et al. 2002). This enabled the researcher to continuously review the methodology (particularly the selection and application of instruments) with collaborative review and intellectual inquiry from key stakeholders and subject matter experts.
- The research approach was implemented within a single case study, which enabled intensive analysis, while the iterative action research platform enabled continuous review of validity, reliability and generalisability (Yin 2009).

Research approach	Knowledge claims	Strategy of Inquiry	Method	Use in research
Quantitative	Postpositivist assumptions	Experimental /Quasi-experimental design	• Predetermined • Closed-ended questions • Performance, attitude, observation and census data • Statistical analysis	• Tests or verifies theories or explanations • Identifies variables to study • Relates variables in questions or hypotheses • Uses standards of validity and reliability • Observes and measures information numerically • Uses unbiased approaches • Employ statistical procedures
Qualitative	Constructivist assumptions Advocacy/ Participatory assumptions	Ethnographic design Narrative design	• Emerging methods • Open-ended questions • Field observation, document data • Text and image analysis • Open-ended interview and audiovisual data • Text and image analysis	• Positions himself of herself collects participant meanings • Focuses on a single concept or phenomenon • Brings personal values into the study • Studies the context or setting of participants • Validates the accuracy of findings • Makes interpretations of the data • Creates an agenda for change/reform
Mixed Methods	Pragmatic assumptions	Mixed methods design	• Both predetermined and emerging methods • Both open and closed ended questions • Open-ended observations • Multiple forms of data drawing on all possibilities • Statistical and text analysis	• Collects both quantitative and qualitative data • Develops a rationale for mixing • Presents visual picture of the procedure in the study • Employs the practices of both qualitative and quantitative research

Table 18: Summary of research approaches

Source: Yutachom & Khumwong (2004)

4.5 RESEARCH STRATEGY: CASE STUDY

As a respected expert on research design (especially case studies) Robert Yin (Yin, 2009) discusses five major research strategies and the justification for selecting the most advantageous based on three conditions or questions (as shown in Table 19). Accordingly, the 'research question form', the 'requirement to control behavioral events' and the need to 'focus on contemporary events' are significant consideration criterion of a research strategy selection (Yin 2009; Amaratunga et al. 2002).

Research Strategy	1. Research question form	2. Requirement to control behavioral events?	3. Focus on contemporary events?
Experiment	How, why?	Yes	Yes
Survey	Who, what, where, how many, how much?	No	Yes
Archival analysis	Who, what, where, how many, how much?	No	Yes/No
History	How, why?	No	No
Case study	How, why?	No	Yes

Table 19: Conditions for different research strategies
Source: (Yin 2009)

Amaratunga et al. (2002) and Amaratunga & Baldry (2001) relate Yin's assertions to the built environment, stressing that the research strategy should be selected objectively based on the situation. Moreover, they insist that strategy selection is further complicated by the fact that each strategy has exclusive approaches to data collection and analysis. Furthermore, the individual characteristics of the strategy may overlap in certain areas consequently Yin's questions could avoid disparity between the desired research goals and the selected research strategy.

Therefore, the fundamental step to differentiate between the numerous research strategies is to classify the research question. In the context of this study, Yin (2009) stresses that some 'what' questions are exploratory in nature, as a result provide adequate justification to conduct an exploratory study using any of the five research strategies listed in Table 19. The core goal of such study is to *'develop pertinent hypotheses and propositions for further inquiry'* (Yin 2009, p.9). In contrast, the second type of 'what' questions actually require an inquiry into 'how many' or 'how much', in these instances a case study based strategy would not be beneficial since a survey or archival methodology is more suited (Yin, 2009).

As a result, based on the fundamental exploratory research question of this study, all five research strategies are applicable, however since it is not a requirement to ‘control behavioural events’ nor make inquiries into ‘how many/much’, but there is a need to ‘focus on contemporary events’, a case study research design appears most appropriate for this study.

The value of using case study design has been systematically discussed and defended in the literature, especially by Yin (1994; 2009), and is no longer considered the ‘ugly duckling’ of research design (De Vaus, 2001). Essentially, case studies differ from other designs *‘in that they seek to achieve both more complex and fuller explanations of phenomena’* (De Vaus, 2001, p.221).

A case study is considered as a detailed examination of an event, or the study of an object, that exhibits the characteristics of some acknowledged theoretical principles (De Vaus, 2001; Amaratunga & Baldry, 2001). Similarly, Amaratunga et al. (2002) emphasise the defintion given by Yin (2009) as an empirical investigation that explores present-day phenomenon that are functioning in a real-life context. Therefore, the focal point of case study based research design involves intensive analysis of the phenomenon under investigated with the principal objective of *‘understanding the dynamics present within single settings’* (Amaratunga et al. 2002, p.26; Amaratunga & Baldry 2001, p.99)

However, it does not necessarily have to be a single setting. As emphasised by De Vaus (2001) and Yin (2009), case study design can comprise of a single case or multiple cases, consequently there is no predefined or correct number of cases to be incorporated into a case study design. The key factor in establishing the number of cases will be the precision with which the propositions are being examined (De Vaus, 2001) since this will provide the significant advantage associated with case materials, namely the rich and extensive comprehension of reality, which is paramount for research in the built environment (Amaratunga & Baldry 2001).

4.5.1.1 Case Study Selection

The research case site was set within one of the UK major government based buildings with total area of 86,000sqm and capacity to accommodate over 3,300 workstations. Since it is highly secure building, some site-specific information including its name and location as well as photography had to be omitted in order to follow the research ethics.

Whilst the case study was essentially a convenience case, it did have many characteristics that could be generalised to other cases within the built environment. Firstly, the case study was a Private Finance Initiative (PFI) project with a long-term service concession (30-years starting in year 2000). Therefore, like most buildings the assets are considered aging (Mobley 2002; Chanter & Swallow 2007).

Secondly, the PFI service provision is for total FM services (soft and hard) with a contract arrangement that requires maintenance to be undertaken and replacement equipment/parts installed when required (maintenance budget of circa £4 million per annum). This is a common feature of FM PFI contracts in the built environment and results in the application of time-based maintenance policies (planned preventative and/or corrective) (Chanter & Swallow 2007; RICS 2009). Finally, at the end of contract the assets will transfer to the client for nil consideration, a common feature of PFI arrangements (Chanter & Swallow 2007). Consequently, the contract contains a hand-back provision that requires the assets to continue to meet the operational specification for a period of two years after the end of the contract. Therefore, the ability to provide evidential condition of assets using CBM will reduce financial risk to shareholders.

Additionally, the case has a few advantages that will benefit overall implementation of the research study. Firstly, due to the critical service function of building, most of the assets have a duty/standby setup (i.e. two identical assets, one operates while the other is on standby and a rotational operations strategy is applied). This provides a unique opportunity to compare/contrast maintenance and operations strategy and impacts on like for like assets. Secondly, there is a strategic drive to explore innovative maintenance management policies towards creating an exemplary service delivery on site. Consequently, a proposal to investigate exploratory CBM techniques is more receptive to end users at all level of the PFI involvement (strategic, tactical and operational levels).

4.5.1.2 Asset Scope

The overall scope of this research project specifically included all critical rotating HVAC components, namely motors, pumps and air handling units (AHU) (83 individual, 44 sets). Such rotating assets are the most important appliances in majority of industries, including the built environment. For example, although there are several types of pumps (including turbo, propeller and positive displacement), the centrifugal pump used in buildings HVAC systems is considered as one of the simplest and most important pieces of machinery, frequently referred to as the ‘workhorse of the industry’ (Pump-zone, 2012). Detailed asset and event information is available in Appendix A.

The accompanying existing asset maintenance protocol is part of the scheduled (time-based) PPM servicing and monitoring processes based on equipment manufacturers recommendations or industry standards (i.e. SFG20). This includes monthly checks, more robust three-monthly service and finally a detailed annual service. Additionally in case of breakdown, the assets undergo Corrective Maintenance (CM). All activities are recorded on the Computer Aided Facilities Management (CAFM) system, stipulating the time, date, detail of the asset, location, generic technical information, detail of the faults as well as resolutions (provides evidence and accountability). Appendix B details the PPM actions undertaken on the assets.

4.6 STRANDS, METHODS AND INSTRUMENTS

The field of mixed method research approach contains a variety of typologies or models (Creswell 2003; Teddlie & Tashakkori 2006; Bryman 2006). One of the fundamental objectives of these typologies is to assist the researcher in deciding 'how to proceed' with the design of a mixed method approach, i.e. which path should be taken to accomplish the research goal. Moreover, they enable a common language and organizational structure to be established (Creswell 2003; Teddlie & Tashakkori 2006).

Teddlie & Tashakkori (2006), present a '*Methods-Strands Matrix'* for determining the most appropriate typology to use. This matrix proposes four types of design typologies, namely sequential, concurrent, conversion and fully integrated. Using this process, a multi-stand mixed method typology which is implemented sequentially was deemed appropriate for this study (as shown in Figure 25), based on the following characteristics:

- The study was conducted over numerous strands that included interchanges of qualitative and quantitative methods.
- There is a chronological and pre-specified order of occurrence (for at least two strands).
- The methods implemented within the strands holistically integrate and contribute towards the overall aim of the research study.

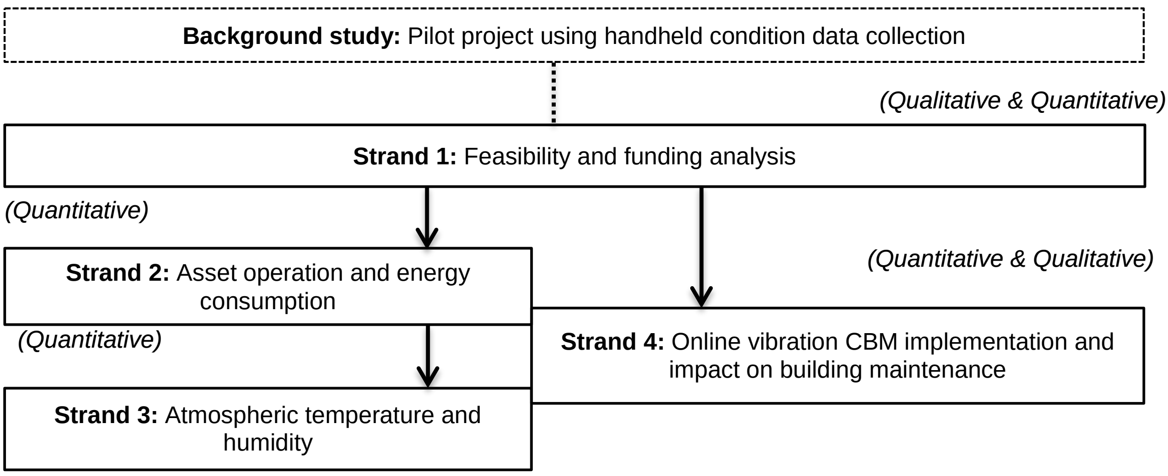


Figure 25: Multi-stand squential mixed method typology utilised for this study

4.6.1 Feasibility and Funding Justification (Qualitative and Quantitative)

Description: In-line with the recommendations and guidelines of ISO 17359 (2011), Shin & Jun (2015) and findings of pilot study evaluation, there is a requirement to undertake a comprehensive analysis of the technical feasibility and funding. This is also described as 'Cost/Benefit' Analysis by Mills (2011) and supported throughout literature as the first logical step in considering predictive maintenance techniques (Shin & Jun 2015; Verma & Subramanian 2012; Al-Najjar 2012).

Aim of the study: In the overall context of this research, the core aim of this in-depth analysis is to establish technical and economical investment feasibility in the specific domain of the built environment and the selected rotary assets.

Associated instrumentation and implementation approach: Structured interviews were undertaken with relevant end users (managers and engineers) to collect the necessary time and cost information. Additionally, a quantitative approach was used to analyse a variety of fundamental documents relating to the current and forecasted positions. Extensive literature surveys and research into industry best practice was also undertaken to ensure assumptions, findings and theories were grounded.

Key outputs: Based on the results of this strand (Chapter 5), a comprehensive report was produced that contained detailed analysis of core Operational Expenditure (OpEx) and Capital Expenditure (CapEx) associated with the assets in scope. The analysis considered costs, savings and opportunities in relation to the whole life of the PFI contract. A new RCM-customised maintenance strategy was proposed which incorporated existing time-based maintenance (scheduled PPM) to be complimented with real-time vibration based condition monitoring and statistical data analysis. The findings from this study contribute directly towards research sub-question 1.1 of this research project.

The presentation of results is included in Chapter 5, along with a more detailed explanation and analysis of the processes by which this part of the study was implemented.

4.6.2 ASSET OPERATION AND ENERGY CONSUMPTION DATA (QUANTITATIVE)

Description: The Buildings Management System (BMS) has the capability to continuously monitor operations and energy characteristics of assets. The associated data will be an accurate reflection of the hours of operations and the consumption of electricity.

Aim of the study: This strand is aimed at validating the operations strategy for the selected asset and understanding the consumption of electricity associated with each asset.

Associated instrumentation and implementation approach: Reports were setup on the BMS to monitor and output specific data points every five minutes. The raw data was accumulated on the server and consolidated into a weekly CSV file that was emailed to the researcher.

Key outputs: Every week the researcher extracted the data from the emails and created a database for analysis, the final analysis was conducted on a significantly large dataset covering a years worth of data collected every five minutes.

Details regarding the data acquisition and processing, as well as the results for this strand are presented in Chapter 6, section 6.2.

4.6.3 ATMOSPHERIC SENSOR DATA (QUANTITATIVE)

Description: Siemens (QFA 2020) temperature and humidity sensors will be installed to acquire this dataset. These devices have the necessary accreditations and approval for installation in this building. The readings will be hardwired directly into the BMS. Additionally, remote data loggers (i.e. TinyTalk and handheld device) will be utilised to ensure reliability and accuracy of the readings.

Aim of the study: This strand is aimed at establishing the conditions within which the assets are operating.

Associated instrumentation and implementation approach: Reports were setup on the BMS to monitor and output the temperature and humidity data points every five minutes. The raw data was accumulated on the server and consolidated into a weekly CSV file that was emailed to the researcher.

Key outputs: Every week the researcher extracted the data from the emails and created a database for analysis, the final analysis was conducted on a significantly large dataset covering a years worth of data collected every five minutes. Details regarding the data acquisition and processing, as well as the results for this strand are also presented in Chapter 6, section 6.2.

4.6.4 ONLINE VIBRATION MONITORING AND ANALYSIS (QUALITATIVE)

Description: A real-time (online), commercial off-the-shelf (COTS) vibration monitoring and analysis solution will enable continuous monitoring of key detectable faults induced by mechanical vibrations as identified in the background pilot study.

Aim of the study: The aim of this strand is to establish viability and practicality associated with implementing online vibration monitoring for building maintenance decision-making. It will also ascertain the condition data of the assets in scope, i.e. whether there is a fault on the asset or not.

Associated instrumentation and implementation approach: The installation of 166 vibration sensors (accelerometers) on critical assets (see Appendix A) located in six different parts of the building (basement and roof areas). The sensors will be wired to vibration units on the wall and the units will be connected to four severs where data will be collected analysed in-line with ISO Standards.

Key outputs: The installation and integration will provide a tool to continuously monitor the condition of asset and implement Condition-based Maintenance.

4.6.5 BUILDING MAINTENANCE: CBM APPLICATION (QUALITATIVE: ETHNOGRAPHY OBSERVATION)

Description: This strand will focus on describing and interpreting the social world through firsthand experience of the field (Saunders et al. 2009). In order for CBM techniques to be applied successfully and effectively, the core component requires attention and integration (Kobbacy & Murthy 2008; Mobley 2002; Sondalini 2006).

Aim of the study: This strand will identify the fundamental impacts of implementing CBM tools in building maintenance.

Associated instrumentation and implementation approach: Observations will be conducted throughout the four years of the research project. This is deemed appropriate particularly since the researcher is immersed in the research settings and sharing peoples lives (i.e. became a member of the organizational team), therefore is able to attempt understand social behavior and explain meaning (Saunders et al. 2009). More specifically, the participant observation method is selected as this involves direct interpretation of behavior and organizational culture using systematic observations, description, recording and analysis (Saunders et al. 2009).

Key outputs: The use of ethnographic observations will enable this study to *'gain insights about a particular context and better understand and interpret it from the perspective(s) of those involved'* (Saunders et al. 2009, p.150). The observations will be related to and analysed in-line with the three core levels of maintenance management identified in the literature (Strategic, Tactical and Operational) (Kobbacy & Murthy 2008; Mobley 2002; Milje 2011). This will also provide a method to generalise the findings of the study to ensure it can be replicated through a process of continuous improvement and lessons learnt (Yin 2009).

4.7 DATA ANALYSIS PROCEDURES AND INTERPRETATION METHODS

Data collection through mixed method instrumentation needs a variety of analysis concepts and approaches that can integrate both qualitative and quantitative aspects. The techniques used to undertake the data analysis are outlined below. The specific details and application are further discussed in the appropriate analysis and synthesis sections of the thesis.

4.7.1 MICRO-LEVEL (WITHIN-STRAND) DATA ANALYSIS

4.7.1.1 Statistical Analysis (Descriptive and Inferential)

In conjunction with built environment research traditions, the study has a strong core of quantitative data (Amaratunga et al. 2002; Amaratunga & Baldry 2001). Therefore, statistical analysis methods were applied on data collected as part of the feasibility and funding analysis (strand 1), asset operation and energy consumption (strand 2), atmospheric temperature and humidity (strand 3) and vibration condition monitoring (strand 4).

The applied statistical method contemplated the type and classification of data, as highlighted by Fidler (2002) and Johnson et al. (2014) these typologies include descriptive and inferential.

Descriptive statistic methods expose associated patterns that assist in describing and/or summarizing the raw data into meaningful information, for example measures of central tendencies or spreads and frequencies (Fidler 2002; Johnson et al. 2014; Laerd.com 2014). In the context of this study, descriptive statistic approaches are significant due to the large quantity of raw data being collected, managed and analysed in various strands. As stressed by Johnson et al. (2014), such situations of raw data are challenging to manage, summarise and visualise without the application of descriptive methods, which enable simpler explanations of the parameters and population.

However, this type of analysis does not enable conclusions to be made beyond the analysed dataset or hypothesis to be tested on generalised population. Consequently, inferential statistics (such as logistics regression) is applied to enable predictions (inferences) to be made relating to the estimation parameters that are dependent on the sampling strategy and/or randomization features (Fidler 2002; Johnson et al. 2014; Laerd.com 2014).

4.7.1.2 Action Research Spiral (Iterative and continuous validity and reliability scrutiny)

As part of the action research platform, the data analysis methods, outputs and quality were consistently and iteratively scrutinised by the monthly Research Board to validate practical understanding, application and continuous improvements. Therefore, end users with 'what-if' reflections regularly reviewed both the quantitative and qualitative datasets, as well as the analysis methodologies of each strand and the initiation of the next strand (Altrichter et al. 2002).

4.7.2 MACRO-LEVEL (BETWEEN-STRANDS) INTEGRATION: TRIANGULATION

The integration and analysis of data from the various strands/phases is referred to as macro-level techniques (Raslan 2010). Triangulation is the main technique applied at this level. In a paper specifically discussing definitions of mixed method research, Burke Johnson et al. (2007, p.114) highlight that triangulation relates to the *'combination of methodologies in the study of the same phenomenon'*. The key attributes of triangulation relating to forms, application scales and outcomes are extensively discussed in the literature and summarised in Table 21.

In the context of a case study based design, the process of triangulation is achieved by using multiple data acquisition methods and sources (Yin 2009; Thurmond 2001; Amaratunga & Baldry 2001). Consequently, triangulation ultimately requires data to be collected via mixed methods and subsequently combined to firstly compliment and secondly enable further validity and reliability conclusions and assurances to be extracted (Yin 2009; Modell 2009; Johnson et al. 2014).

Attributes	**Description**
Forms of Triangulation:	
Data	Data is gathered through multiple sampling and collection strategies, which allows the datasets to cover variety of times, situations and interest focus.
Investigator	Numerous researchers are used to gather and interpret the data.
Theoretical	Multiple theoretical positions are used for the interpretation of collected data.
Methodological	Utilisation of multiple data collection instruments and methods (e.g. interviews, documents, questionnaires, sensors), especially in relation to amalgamating mixed-method research.
Scales of Application:	
Within-method	Apply same instrumentation customised to explore a particular issue, for example adding thresholds to datasets or scales to questionnaires.
Between-method	Apply research methods that enable contrasting, e.g. observations and sensor data, or interviews and questionnaires.
Possible Outcomes:	
Collaboration	Results of all research methods demonstrate 'same' conclusion.
Contradiction	Results from one research method (e.g. questionnaires) conflicts with another (e.g. observations)
Elaboration	Data analysis and finding of one method epitomises the ways in which the finding of another method applies.
Complementarity	Individually the results from different methods contrast, yet combined together they produce insights.

Table 20: Key attributes of triangulation

Source: Adapted from (Burke Johnson et al. 2007; Raslan 2010; Morgan 1998; Bryman 2006; Brannen 2005; Davis & Meyer 2009; Amaratunga & Baldry 2001; Saunders et al. 2009)

4.8 QUALITY OF RESEARCH: ISSUES OF VALIDITY AND RELIABILITY

One of the key attributes of mixed method research is the methodological strategy, which provides a better standard of conclusions through amalgamating strengths of multiple methods and reducing risks that arise when only one method is used (Azorín & Cameron 2010; Teddlie & Tashakkori 2006). Therefore it is particularly superior in terms of validity and reliability when attempting to understand complex phenomena (Burke Johnson & Christensen 2014).

Nevertheless, according to Yin (1994; 2009) and reinforced by Amaratunga & Baldry (2001), there are four types of design validity 'tests' that all research is required to comply against. Table 22 summarises the tests in relation to the tactics which can be applied in the context of case study based research design. As stressed by Yin (2009), for case studies, each test requires explicit attention not just at the begining (research design stage), but throughout the conducting of the research. Therefore, Table 22 also highlights the phases in which the tactics are recommended to be applied. Consequently, in conjunction with ensuring this study conforms to these tests, the validity and reliability of this research is further reinforced by the iterative action research platform which ensures the tactics are applied accordingly through collective reflection and intellectual inquiry.

Test and Description	Case Study Tactic	Phase in which tactic occurs
Construct Validity: determining correct operational measures for the concepts being studied.	Use of multiple sources of evidence. Establish chain of evidence. Have key informants review draft report.	Data collection. Data collection. Composition.
Internal validity: establishing a casual relationship (certain conditions are shown to lead to other conditions). Only relevant for explanatory or casual research, not descriptive or exploratory case studies (Yin, 2009).	Do pattern matching. Do explanation building. Address rival explanations. Use logic models.	Data analysis. Data analysis. Data analysis. Data analysis.
External validity: Determining the domain to which a study's findings can be generalised.	Use theory in single-case studies. Use replication logic in multiple case studies.	Research design. Research design.
Reliability: Demonstrating that the operations of a study (e.g. data collection methods) can be repeated, with the same results.	Use case study protocol. Develop case study database.	Data collection. Data collection.

Table 21: Validity and reliability in case study research
Source: adapted from (Amaratunga & Baldry 2001) based on (Yin 2009; Yin 1994)

4.8.1 RESEARCHER CERTIFICATION: VIBRATION ANALYST

The arduous sphere of CBM data analysis, especially the application and analysis of vibration condition monitoring, is a very specialist subject that requires knowledge and expertise to be acquired via professional training in order to accordingly collect, analyse and evaluate vibration sensor data. Therefore, as part of this project the researcher completed the relevant industry certifications to qualify as a professional Vibration Analyst:

- Successful completion of both *Category 1 and 2 Vibration Analysis and Condition Monitoring* courses and exams (minimum pass requirement at 75% and 70%).
- The courses comply with and exceed the relevant governing standard: ISO 18436-2 (2003) - *Condition monitoring and diagnostics of machines - Requirements for training and certification of personnel - part 2: Vibration condition monitoring and diagnostics.*
- The British Institute of Non-Destructive Testing (BINDT) certifies the courses and ensures all Vibration Analysts qualifications are registered.
- The researchers certification is registered under the BINDT reference 322801.

4.9 ETHICAL PRACTICE

Table 23, summarises the key ethical issues relating to business research. Research ethics refers to the morals and responsibilities of conducting research. Moreover, it considers the suitability of the researchers behaviour (i.e. morally defensible) in respect to the rights of the individuals affected by the research (Saunders et al. 2009).

Key ethical issues:
Privacy of possible and actual participants
Voluntary nature of participation and the right to withdraw partially or completely from the process
Consent and possible deception of participants
Maintenance of the confidentially of data provided by individuals or identifiable participants and their anonymity
Reaction of the participants to the way in which you seek to collect the data
Effects on participants of the manner in which you use, analyse and report on data
Behaviour and objectivity of the researcher

Table 22: Key ethical issues in research

Source: (Saunders et al. 2009)

However, since the researcher is likely to be affected by ‘broader social norms’ of the contextual setting, it is difficult to establish precisely what actually constitutes ‘morally defensible’ behaviour beforehand (Naimi 2007; Saunders et al. 2009). Nevertheless, in the context of this study, regardless of the social norms of behaviour in FM, the action research platform enabled the research intent information to be easily delivered to all individuals and/or organisations involved. Additionally, approvals to participate were obtained from individuals directly involved with the research.

The key ethical issues in this study relate to Strand 4, ethnographic observations. As stressed by Saunders et al., (2009) and Naimi (2007), the method of conducting ethnographic research requires access to data collection without appropriate consent from the observed, as a result the ethical issues need to be considered.

The primary aim of the ethnographic observations seeks to identify the fundamental impacts of implementing CBM tools in building maintenance, therefore role of the researcher was not concealed, i.e. the researcher was a ‘observer participant’ (Saunders et al. 2009). However, this strategy raised ethical concerns which need to be considered, the following ethical rationale was used for conducting the ‘observer participant’ strategy:

- The observations were undertaken within the case study, which was participating in numerous other strands of the research project.
- Since all levels of the case study consented to participate, it is believed likely that there would be no objection to the observational phase of the research.
- Throughout the study, the job title given to the researcher is ‘Research Engineer’, and all participants were aware of the researchers role.
- The observational element does not seek to infringe upon personal activities or beliefs of the individuals involved in this case study.

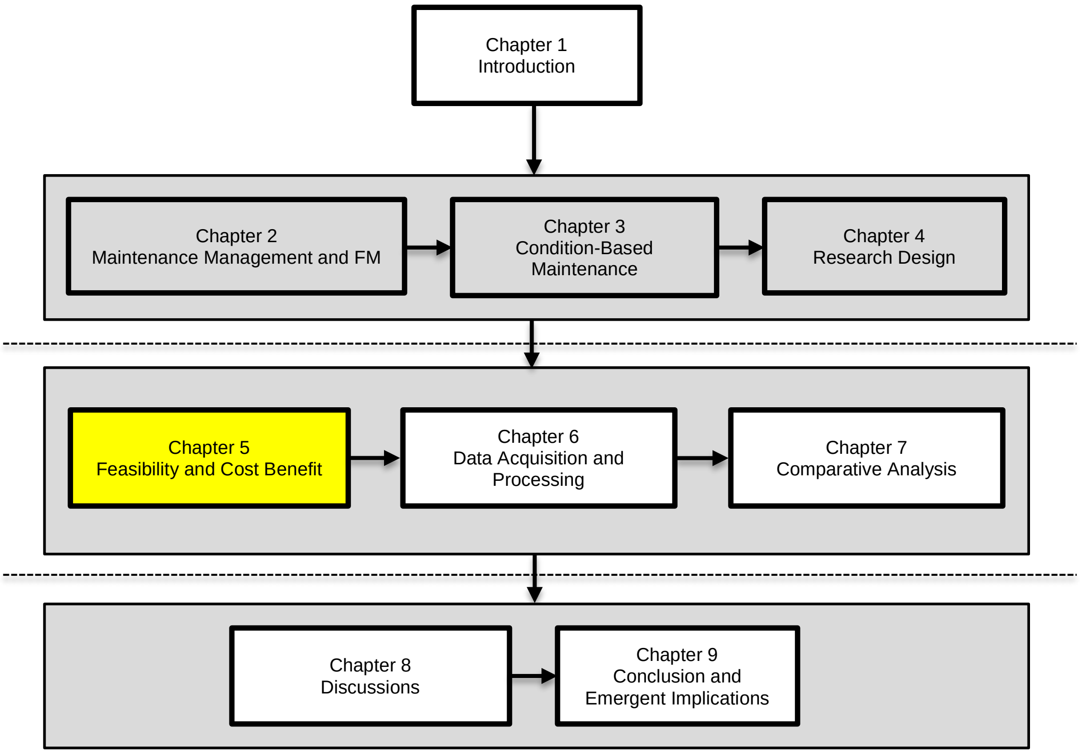
4.10 BOX 4: SUMMARY OF RESEARCH DESIGN

This chapter details the design and approach for the research, in summary:

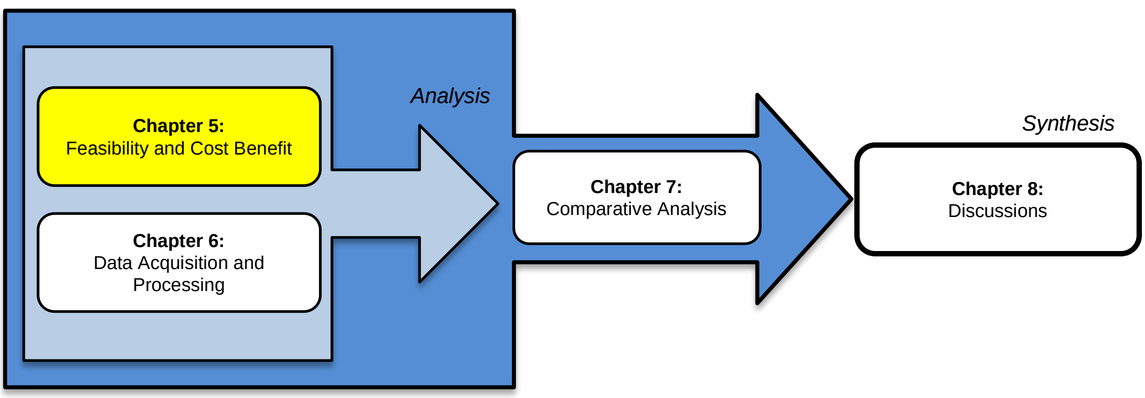
- The research is conducted through an action research platform:
    - Since the nature of FM is practical, research and practice is synergistic.
    - The action research platform is traditionally used in FM; it attempts to bridge the gap between research and practice.
    - This platform enabled industry and academia collaboration through a four-year partnership in which the researcher was employed at the research site full-time as a Research Engineer.
    - Weekly research meetings and monthly research board meetings with senior management, professors and other doctorate researchers were conducted to enable continuous scrutiny, validation and intellectual inquiry (as per the action research spiral).
- A mixed methodology research framework is adopted:
    - Built environment research has a tendency of being dominated by a strong quantitative research.
    - Research highlights mixed methods as an alternative, and possible superior approach within the built environment.
    - The rationale for a mixed methodology considered the domain of the study, the research objectives and the nature of the research subject in conjunction with the action research platform.
- Case study based research strategy is adopted:
    - Based on the exploratory nature of the research question.
    - A need to focus on contemporary events, without controlling behaviours.
    - A single but appropriate case is selected and necessary rotary assets scoped for investigation.
- A multi-stand mixed method typology is implemented which has mutiple stands:
    - The multiple qualitative and/or quantitative stands combine to validate the overall research objectives and fundamental research question.
- The proposed data analysis and integration is undertaken at two levels (within-strand and between-strands) using a variety of approaches to ensure validity and reliability:
    - Micro-level: Statistical analysis and action research cycles.
    - Macro-level: Triangulation strategy is used to integrate the various strands.

The next chapter will undertake a comprehensive technical feasibility and cost benefit analysis to enable answering the research sub-question 1.1.

5 TECHNICAL FEASIBILITY AND COST BENEFIT ANALYSIS



This chapter presents a comprehensive investigation and analysis into the maintenance cost, savings and opportunities associated firstly with the existing practices and secondly with proposed CBM solution. It highlights the methods the researcher implemented to establish the current baseline cost and opportunities which are subsequently cross-examined against the technical feasibility costs to determine whether CBM based predictive maintenance implementation can be financial justified on the case study.



5.1 BACKGROUND AND METHOD OVERVIEW

In conjunction with the recommendations in the literature (including Shin & Jun (2015); Jardine et al. (2006); Veldman, Klingenberg, et al. (2011); Al-Najjar (2012)) and guidelines of ISO Standards (such as 17359 (British Standards Institution 2011), 13381-1 (ISO 2004), 13373-2 (ISO 2005)), there is a requirement to carry out a comprehensive analysis of the technical feasibility and economic justification prior to implementing CBM policies such as online vibration monitoring and analysis.

As stressed in ISO 17359 (2011) (British Standards Institution, 2011) undertaking the preliminary feasibility and cost benefit analysis helps determine accurate benchmarks and key performance indicators (KPI), which can be used to measure the overall effectiveness of a condition monitoring installation. Furthermore, the cost benefit analysis ensures considerations are made towards total costs (including lifecycle and lost production), as well as consequential damage, warranty and insurance details.

Therefore, this section provides the foundations for the in-depth action research conducted using the case study in the subsequent chapters.

This chapter fulfils objective 1 of this thesis:

> *Undertake a feasibility study to determine key costs, savings and potential opportunities of implementing predictive maintenance (online vibration condition monitoring).*

Accordingly, this chapter is driven by the following research question (1.1):

> *What are the cost, savings and opportunities of implementing CBM?*

The research detailed in this chapter are published in International Journal of Facility Management (Amin et al. 2015), and presented at the International Facilities Management Association (IFMA) 2015 Research & Academic Track (IFMA 2015).

5.1.1 METHODOLOGY: OVERVIEW

The methodical process of collection, analysis and synthesis of data during this strand is demonstrated in Figure 26. The key characteristics are follows:

- **The technical feasibility** analysis was undertaken in two stages, firstly the comprehensive literature survey undertaken in Part A of this thesis (see Chapters 2 and 3) was further enhanced where necessary, and secondly specialist industry consultants were brought in to conduct surveys, provide guidance, support and quotations.
- **The cost benefit** elements were broken down into two types of expenditures, namely Capital (CAPEX) and Operational (OPEX). These were established using various research methods (as shown in Table 24).
- The analysis and findings from both elements were iteratively presented to the EngD board. The final **business case report** for investment was developed and analysed in conjunction with the EngD Board and subsequently presentation to the two sets of Board of Directors for approval.
- **Successful approval** of the business case enabled overall project implementation.

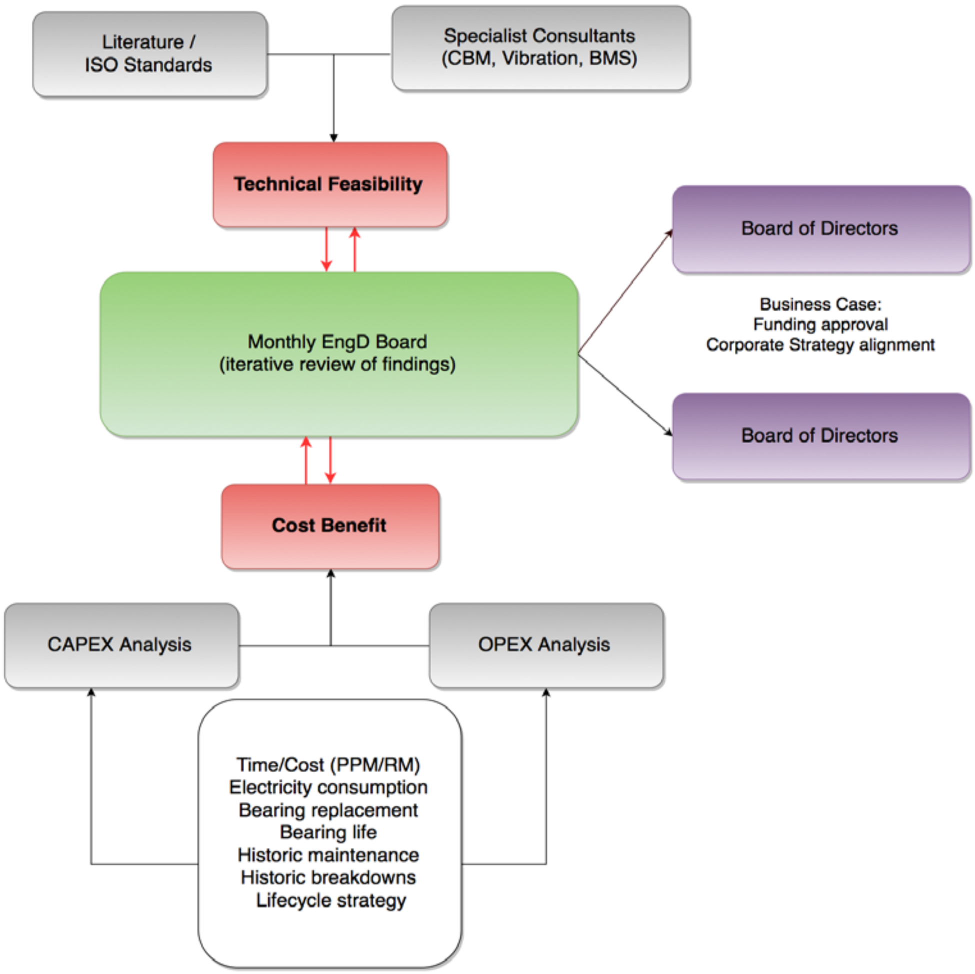


Figure 26: Process overview of technical feasibility and cost benefit analysis

5.1.2 STUDY METHODOLOGY: MIXED METHOD DATA COLLECTION

In-line with the mixed method research methodology, the data was collected using various instruments (as detailed in Table 24):

- **Interviews** - the guidelines outlined by (Teddlie & Tashakkori 2006) were used to generate a framework. Resulting in the utilisation of *'interview guide approach',* which enabled topics to be specified and the researcher to adjust the question order and wording depending on the participants (i.e. engineers, managers, senior managers, consultants). Fundamentally, this approach was less formal in comparison to scripted interviews and supported the action research context (Azorín & Cameron 2010).
- **Interrogation of the systems** – As highlighted throughout literature, the background event data is crucial in conducting the required analysis (Veldman, et al. 2011a; British Standards Institution 2011; Jardine et al. 2006). Therefore various systems were scrutinised to acquire the necessary datasets.
- **Specialist consultants** - This contributed to technical feasibility and implementation cost assembly.

OPEX Costs:	**Data and collection method**
PPM:	Interviews with Engineers to capture the time it takes to carry out the three types of PPM. Interviews with Admin Manager to capture the time it takes to process the paperwork relating to the maintenance. Interviews with Commercial Manager to capture the employment costs.
RM:	Interviews with Head of Asset Management and Commercial Manager to capture the contractual position of the RM. The VFA Lifecycle planning and budgeting system was interrogated to capture the asset value and install date and life expectancy.
Electricity:	The Building Management System (BMS) was interrogated to capture the Hours of Operations (HrsOp) and kilowatt-hour (kWh) ratings of the assets.
CAPEX Costs:	
Historic failures	Computer Aided Facilities Management (CAFM) System was interrogated to capture the historic maintenance and breakdowns records.
Bearing replacement costs	Computer Aided Facilities Management (CAFM) System was interrogated to capture the associated costs for historic bearing changes.
Planned Lifecycle costs	Interviews with Head of Asset Management to capture the lifecycle replacement strategy.
Technical feasibility and Quotations	Specialist condition monitoring companies were consulted, interviewed and walk-round surveys undertaken to acquire quotations for sensor installations.

Table 23: Summary of mixed method data and collection instruments.

5.2 RESULTS: CURRENT EXPENDITURE POSITION

For the assets in scope, the collected expenditure data is categorised in the context of either OPEX or CAPEX. The following section details the findings for both categories.

5.2.1 OPERATIONAL EXPENDITURE (OPEX)

In the context of this study, OPEX relates to the cost of the following elements:

- PPM labour cost
- RM contractual cost
- Electricity usage cost

5.2.1.1 Labour Cost of PPM

The assets are currently subject to Time-based Planned Preventative Maintenance (PPM) routine. This is undertaken in-line with manufacturers recommendations and/or FSG20 industry standards (in the absence of manufacturers recommendations).

In conjunction with the relevant on site commercial managers (to ensure validity), and using the interviews to collect the necessary data, a model was created to provide a typical example of the cost associated with the labour. The costs appeared to be allocated to two types of labour: Engineers and Admin Staff. The cost models are provided below.

Engineers Cost	
Salary	£32,000
On Costs (33%)	£10,560
Misc cost (training, sick: 15%)	£4,800
Annual Cost of Employment	£47,360
Working days per annum *	221
Day Rate	**£214.330**
Hourly Rate	**£29.56**
(* includes allowances for annual leave, sick leave, bank holiday and training)	
Admin Staff Cost	
Salary	£26,000
On Costs (33%)	£8,580
Misc cost (training, sick: 15%)	£3,900
Annual Cost of Employment	£38,480
Working days per annum *	219
Day Rate	**£175.71**
Hourly Rate	**£24.24**

Table 24: Labour cost for PPM

Subsequently, the amount of time spent on each activity was established (Table 26), which then provided the necessary information to work out the yearly quantity and cost of each PPM (Table 27).

PPM	Engineer time per PPM	Admin time per PPM
Monthly	30mins	15mins
Three monthly	45mins	
Annually	60mins	

Table 25: Time taken to undertake and process PPM

PPM	Quantity	Cost
Monthly	8	£166.70
Three monthly	3	£84.68
Annually	1	£35.62
Total Labour Cost:		**£287.01**

Table 26: Cost to undertake and process PPM

Based on this analysis, the annual labour cost of conducting PPM is £12,628.23 per year (£287.01 per asset).

5.2.1.2 Cost of Reactive Maintenance (RM)

The contractual arrangement for this case mandates that the Reactive Maintenance be based on three per cent of the asset valuation. Therefore, asset valuation is obtained from the VFA Lifecycle planning and budgeting system (£1,539,280.90) and three per cent of this value is used as the RM allowance for this analysis (£46,178.43).

Table 28 provides a breakdown summary of the PPM and RM costs associated with the assets in scope.

5.2.2 SUMMARY OF PPM AND RM OPEX COSTS

Table 28, provides a summary of the costs and additional information obtained from this analysis. The motors associated with the pumps or fans are maintenance inclusively therefore no separate costs are itemised. Additionally, the cost of undertaking proactive maintenance (post CBM implementation) is established for analysis later (i.e. the cost of six 1 monthly PPM).

LOCATION / ASSET		**ASSET INFO**				**ANNUAL PPM**				**ANNUAL RM**	
	Qty	**Install Date**	**Asset Value**	**Age**	**Life Expect.**	**1 monthly cost (x 8)**	**3 monthly cost (x3)**	**12 monthly cost**	**Total Annual PPM Cost**	**Cost of RM (3% value)**	**Proactive Maint. (x6)**
Plant Room A - Pump	4	2004	£138,585.60	10	30	£666.82	£338.73	£142.47	£1,148.02	£4,157.57	£500.11
Plant Room A - Motor	4	2004	£ -	10	15	£ -	£ -	£ -	£ -	£ -	£ -
Plant Room B - Pump	4	2004	£138,585.60	10	30	£ 666.82	£338.73	£142.47	£1,148.02	£4,157.57	£500.11
Plant Room B - Motor	4	2004	£ -	10	15	£ -	£ -	£ -	£ -	£ -	£ -
9th Floor Chilled Water - Pump	12	2004	£415,756.80	10	30	£2,000.46	£1,016.20	£427.41	£3,444.06	£12,472.70	£1,500.34
9th Floor Chilled Water - Motor	12	2004	£ -	10	15	£ -	£ -	£ -	£ -	£ -	£ -
Chilled Water Plant Room - Pump	11	2004	£381,110.40	10	30	£1,833.75	£ 931.51	£391.79	£3,157.06	£11,433.31	£1,375.31
Chilled Water Plant Room - Motor *	16	2004	£173,232.00	10	15	£833.52	£423.42	£178.09	£1,435.03	£5,196.96	£625.14
Roof Area 9&10 - AHU Extract Motor	4	2004	£ -	10	10	£ -	£ -	£ -	£ -	£ -	£ -
Roof Area 9&10 - AHU Extract Fan	4	2004	£146,005.25	10	20	£666.82	£ 338.73	£142.47	£1,148.02	£4,380.16	£500.11
Roof Area 9&10 - AHU Supply Motor	4	2004	£ -	10	10	£ -	£ -	£-	£ -	£ -	£ -
Roof Area 9&10 - AHU Supply Fan	4	2004	£146,005.25	10	20	£666.82	£338.73	£142.47	£1,148.02	£4,380.16	£500.11
(5 Direct Drive pumps - motor only)*											
Sum:	**83**		£1,539,280.90			£7,335.01	£3,726.06	£1,567.16	£12,628.23	£46,178.43	£5,501.26

Table 27: Summary of asset information and maintenance costs

5.2.3 AMOUNT AND COST OF ELECTRICITY

To calculate the annual amount and cost of the electricity associated with the assets in scope, the Building Management System (BMS) was interrogated to capture the scheduled hours of operations (system configured to run a ratio of 50:50 duty/standby), and the kilowatt-hour (kWh) ratings of the assets. Subsequently, based on this data, it was possible to calculate the annual:

- Total kWh consumption.
- Cost per asset using the cost factor (*8 pence per kWh*).
- CO_2 emission per asset (based on factor of 0.44548 kgCO_2 per unit (Carbon Trust, 2014).

The total annual electricity consumed by the assets in scope is in excess of five million kilowatt-hours, as show in Table 29. This costs the site around £409,238.40 annually and the consequent CO_2 emission is 2,278.8 tonnes.

Asset / Location	Scheduled Operation Hours	Electicity (kWh)	Cost	CO2 (T)
Pumps (Basement Chiller)	43,800	3,048,480	£243,878.40	1358.04
Pumps (Roof)	26,280	911,040	£72,883.20	405.85
AHU Fans (Roof)	24,960	472,680	£37,814.40	210.57
Pumps (Basement A)	17,520	424,860	£33,988.80	189.27
Pumps (Basement B)	17,520	258,420	£20,673.60	115.12
Sum:	**130,080**	**5,115,480**	**£409,238.40**	**2278.84**

Table 28: Annual electricity consumption and associated cost and CO_2, by location.

A more detailed analysis, highlights a notably high consumption attributed to assets in the Chilled Water Plantroom (Figure 27), this could be due to assets being larger in size and operating longer hours.

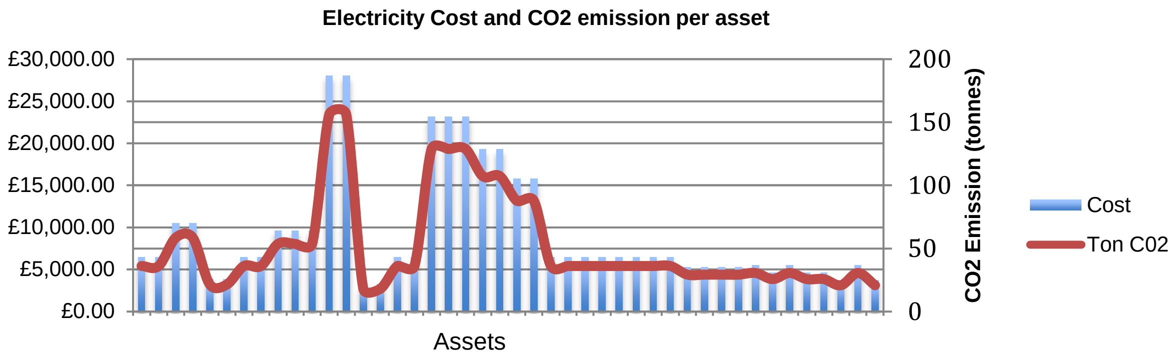


Figure 27: Annual electricity consumption cost and CO_2 emission, per asset

(A detailed scheduled electricity consumption data table is provided in Appendix C)

5.2.4 CAPITAL EXPENDITURE (CAPEX)

The most significant capital cost associated with rotary assets is the replacement of bearings, consequently, there is extensive research highlighting the need to implement CBM to aid detection and diagnosis of bearing failures (as discussed in Chapter 3) (Beebe 1987; Dahmer 2012; Mahamad et al. 2010). This section highlights the historic bearing failures, analysis of life (achieved vs. expected) and potential opportunities associated with implementing CBM.

5.2.4.1 Bearing Life

The basic bearing life (also known as L10) is associated with 90% reliability when built via modern manufacturing methods using high quality materials and operated under normal conditions (as detailed in *IS0 281:2007, Rolling bearings – dynamic load ratings and rating life).*

However, in practice the predicted life may deviate significantly from the basic life, in some documented cases by nearly a factor of five. Research estimates that as many as 91% of all bearings fail to reach their calculated L10 life (Rehmann 2005). The life calculations are sensitive to many factors e.g. operating load, room temperature, lubrication condition / poor lubrication, contamination level, alignment and balancing.

Therefore it will be extremely difficult to precisely establish the used life or the L10 life value for the assets in scope. However, on average there are four sets of bearings (two on motor and two on pump/fan). As a general rule, industry recommendations suggest replacement at approximately 50,000 to 100,000 hours, for example:

"In the case of a ball bearing fan an engineer can expect a useful life of 60,000 - 70,000 hours (L10) under normal operating conditions (-40~50^{C} at 75% RH)" (Orion Fans, 2014)

"Most motor bearings are designed to last for 100,000 hours" (IEN, 2014)

Therefore, it is important to analyse the historic failures and replacement and the hours of life achieved by the bearings relating to the assets in scope.

5.2.4.2 Historic Bearing Replacement

A comprehensive search of the CAFM system was carried out before the implementation of the *'Pilot CBM Project'* (November 2012), which resulted in no record of bearing changes being found for the selected assets. The same interrogation of the system was undertaken as part of this study, which revealed that since then, the following bearing replacements (like for like) have taken place:

Unplanned breakdown changes:

1. November 2012: AHU 17 Supply Fan Motor
    - Total cost of replacing only motor bearings: *£2,208*

Planned proactive changes: *Identified through handheld vibration condition monitoring, optimised then proactively changed ensuring no unplanned failure or service disruption.*

2. August 2013: IT primary pump 23
    - Total cost pump and motor bearing replacement: *£3,195.05*

3. October 2013: Cooling Tower 01 pump 05
    - Total cost pump and motor bearing replacement: *£3,409.75*

4. June 2014: IT Primary pump 19
    - Total cost pump and motor bearing replacement: *£4,898.44*

5. July 2014: IT Primary pump 24
    - Total cost pump and motor bearing replacement: *£2,750.00*

The above findings suggest:

- A notable increase in planned proactive bearing replacements has been undertaken since the introduction of vibration monitoring tools.
- The replacements did not impact core services and the life was optimised with risks being considered before initiating changes.
- Cost of replacement is significant, particularly if numerous replacements are required outside of the planned lifecycle budget.

5.2.4.3 Actual Life Achieved vs. Expected Life

Based on the replacements and the operating patterns of the assets, it is possible to analyse the hours of life achieved by bearings in comparison to the suggestions in the literature of expected life estimates (50,0000 – 100,000 hours), as shown in Figure 28.

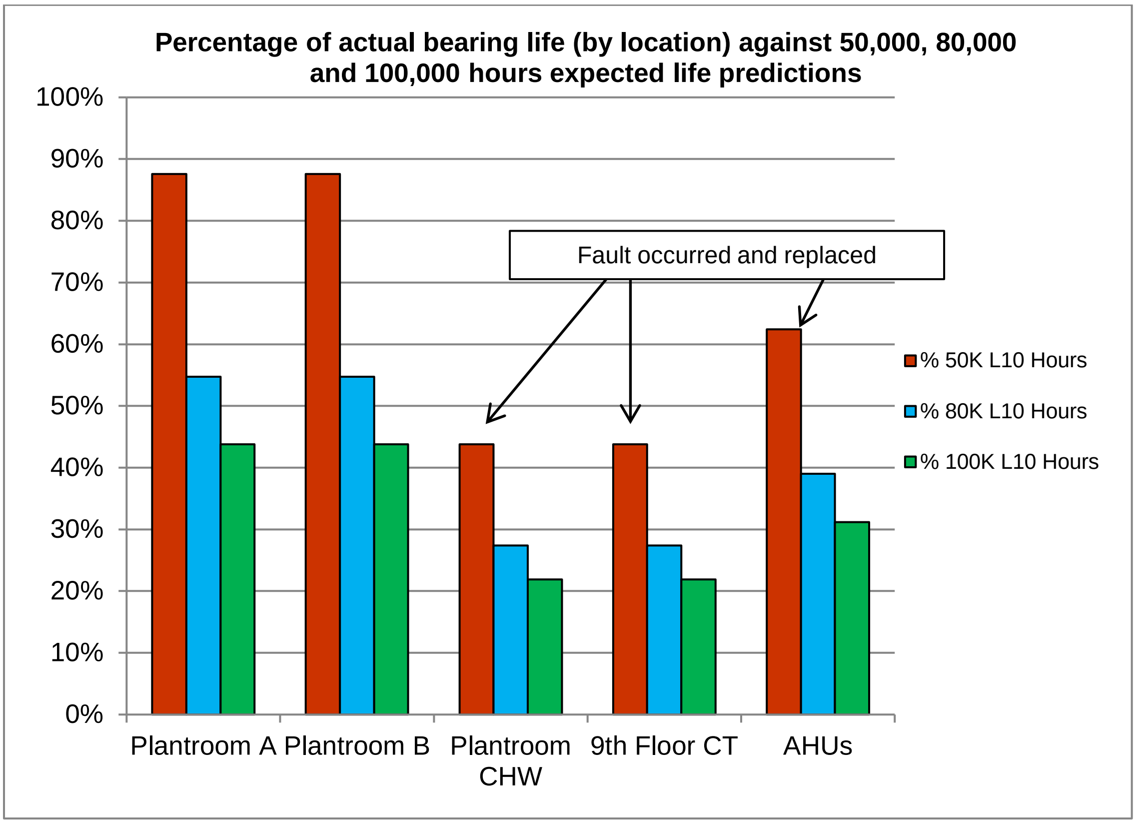


Figure 28: Percentage of actual bearing life (by location) against the expected hours of life predictions.

Figure 28, highlights that:

- The assets in Plantrooms A and B have achieved 88% of the predicted 50,000 hour bearing life without any failure occurrences or replacement need (since install in 2004).
- In contrast there has been a failure in each of the other Plantrooms/areas even though the used life percentage was much less (prior to failure).
- Therefore majority of the bearings are requiring a change (as result of a fault) without reaching the minimum 50,000 hours.

5.2.4.4 Replaced Bearings: Life Achieved

Further analysis of the specific assets that had bearings replaced, showed that the life achieved varied and were all below the 50,000 hours (since the first installation and commissioning in 2004). As shown in Figure 29, the highest life was attained by IT Primary Pump 24 in the Chilled Water Plantroom (42,348 hours), and the lowest at 19,536 hours was the Base Build Cooling Tower 1 Pump 05 in the 9th Floor Roof Area.

Based on this analysis the average life of the replaced bearings is 33,438 hours, which is significantly lower than the life predictions suggested by literature and manufacturer recommendations (Orion Fans, 2014; IEN, 2014).

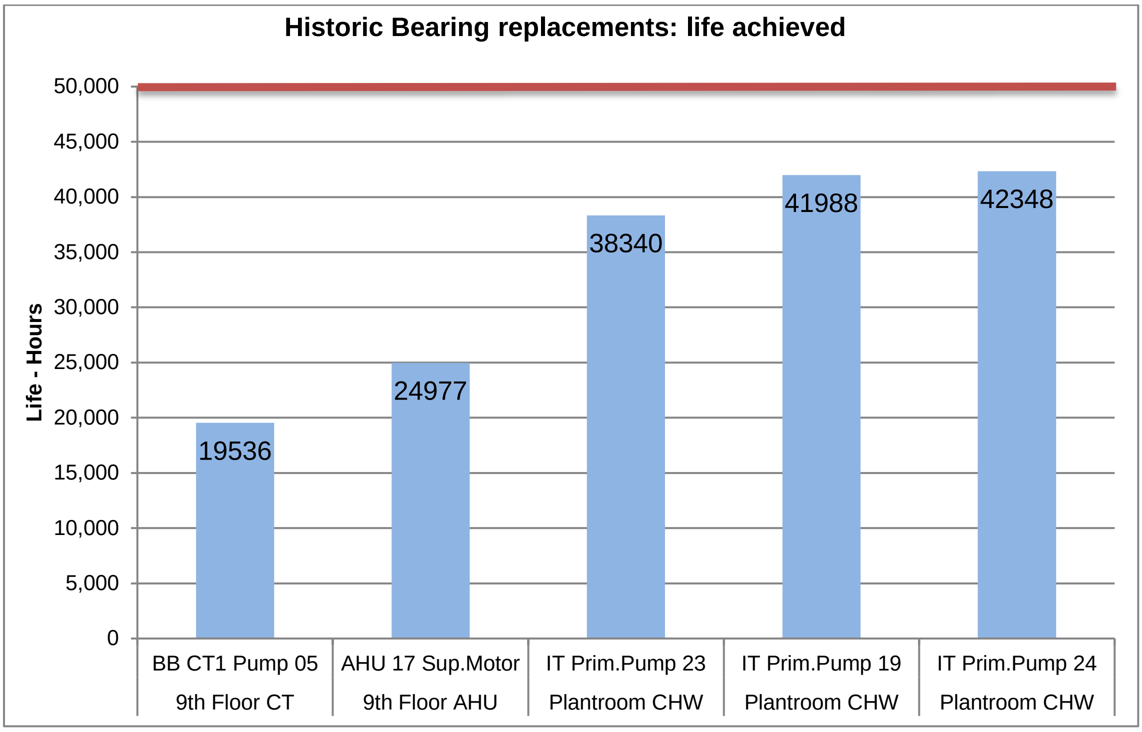


Figure 29: Shows the life in hours achieved from the replaced bearings.

5.3 PROPOSED CBM SOLUTION ANALYSIS

A customised CBM maintenance framework is proposed that focuses on only the critical assets in scope of this study. For the purposes of the following potential impact analysis, it should be noted that this is approximately five per cent of the total rotary assets in the building (i.e. critical to service operations).

5.3.1 OVERVIEW

The proposed solution implements an innovative *RCM-Customised* maintenance concept (Kobbacy & Murthy 2008). It is achieved by firstly upgrade to online monitoring solution and secondly to modify the current maintenance strategy by removing the monthly and three monthly PPM routines, consequently only undertaking one Annual PPM per asset. This will set the precedence for the case site to transition from PPM to predictive CBM when the Defect Liability Period expires. Fundamentally, the proposal changes the maintenance concept, policy and actions in alignment with the corporate strategy, as demonstrated in Figure 30.

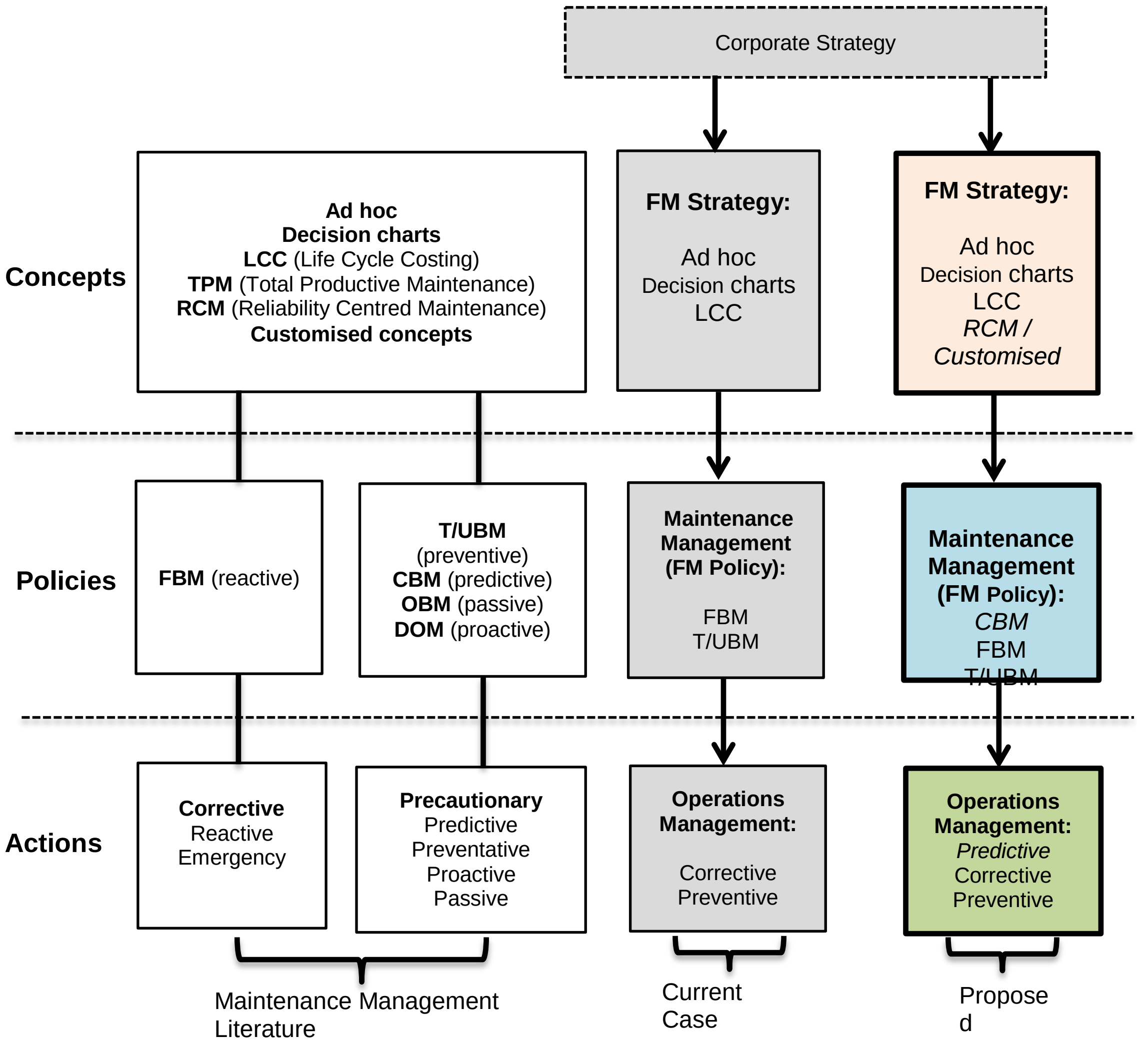


Figure 30: Maintenance actions, policies and concepts commonly applied in FM

Source: Adapted from (Kobbacy & Murthy 2008; CIBSE 2008; RICS 2009)

5.3.1.1 Potential Key Impacts

The proposed solution, which enables continuous monitoring of asset usage and condition parameters, will have the following anticipated impact over the remaining life of the contract (sixteen years):

Reactive Maintenance (RM): The cost of RM is calculated to be £46,178.43 per year (three per cent of asset value from VFA system). By reducing the risk of unplanned breakdowns it is predicted that the value of RM will decrease to £43,869.51 per year towards the end of the contract (overall anticipated decrease of five per cent) (Wallace & Prabhakar 2003; Mobley 2002).

Planned Preventative Maintenance (PPM): Since the assets will be continuously monitored it will be possible to consider the removal of Monthly and Three monthly PPM routines, leaving only the Annual PPM.

Electricity: As a general rule older assets are more susceptible to faults (Mobley 2002; Jardine et al. 2006; Wallace & Prabhakar 2003). Research suggests that a slight vibration induced fault can increase energy consumptions and the lateral load on bearings triggering early failure (e.g. as detailed in Saidur (2010). Furthermore, efficient monitoring and maintenance can contribute up to 20 per cent savings on total energy consumption (Rao 1993). Therefore, continuous monitoring will enable early identification of any vibration-induced faults such as misalignment, looseness and balancing issues. Moreover, the operating data capture and trending from the inverters will allow electricity consumptions to be easily aligned with asset load and efficiency. Therefore a 5%-10% reduction in electricity consumption can be predicted (in-line with most condition monitoring supplier suggestions e.g. SPM Lubmaster, Damalini easy laser alignments).

Whole asset life: Through continuous monitoring, proactive interventions and efficient operation, it is expected that overall whole life in years will be extended by around 10%-15%. The financial savings associated with this life extension is difficult to quantify consequently has been omitted from this analysis.

Proactive Maintenance (ProM): The cost of any proactive interventions (i.e. fault detected on system and visit required to asset) needs to be taken into account. Therefore the cost of bi-monthly ProM intervention will be considered (per asset) to rectify faults identified by continuous monitoring.

5.3.2 TECHNICAL FEASIBILITY AND VALIDITY

As demonstrated in Figure 31, the process of establishing technical feasibility initiated with the comprehensive review of literature (Chapters 2 and 3), which led to the detailed analysis of international standards relating to condition monitoring. Following that, the researcher undertook training and certification. Subsequently, specialist consultants were engaged to provide quotations and installation guidance. Finally, the researcher visited other industry sites to observe use of vibration technologies for condition monitoring.

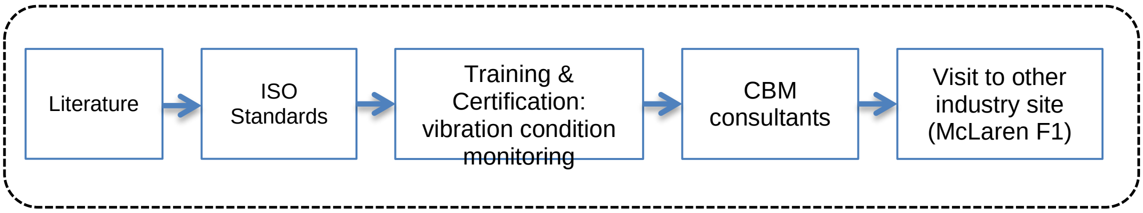


Figure 31: Process of establishing technical feasibility and validity

To establish the technical feasibility of the proposed solution, the researcher engaged with three specialist condition monitoring solution suppliers (identified through Google and existing supplier networks). The scope discussed with the consultant companies involved the implementation of real-time vibration condition monitoring based on the recommendations of:

- BS ISO 17359:2011 – Condition monitoring and diagnostics of machines — General guidelines (British Standards Institution 2011).
- ISO 13373-1:2002 – Condition monitoring and diagnostics of machines – vibration condition monitoring – Part 1: General Procedures (ISO 2002).
- ISO 13373-2:2005 – Condition monitoring and diagnostics of machines – vibration condition monitoring – Part 2: Processing, analysis and presentation of vibration data (ISO 2005).

These three international standards provide the core technical feasibility and validity recommendations covering the whole implementation process. For example, guidance on undertaking feasibility and establishing equipment criticality in ISO 17359:2011, selecting the transducers, measurement parameters and frequency ranges in ISO 13373-1, and processing, analysis as well as the presentation of time and frequency data in ISO 13373-2.

5.3.2.1 Quotations

Table 30, shows the breakdown of all three quotations acquired following several meetings and surveys of assets. The specialist consultant companies were asked to quote with the following considerations:

- **Hardware**: Provision of all hardware such as servers, speed modules and mounted accelerometers that are suitable for the equipment, environment and compliant with ISO recommendations, such recommending frequency ranges of up to 10kHz (ISO 2005; Standard 1998; ISO 2002).
- **Software**: Provision of software to enable detailed data analysis including threshold parameter setup, overall trending, vibration waveforms, spectrums and fault frequency pattern matching (ISO 2005; Standard 1998; ISO 2002).
- **Installation**: Provision to install the cabling, sensors and monitoring units on site. Due to security reasons wireless sensors were unacceptable for installation in the case building.
- **Training and Project Management**: Provision to provide training on the use of the systems and data analysis.

Quote 1	COMPANY 1 (techniques: Vibration & Shock Pulse)	
1.1	Total Hardware	£ 162,645.28
1.2	Total Software	£ 919.67
1.3	Installation	£ 56,083.50
1.4	Commissioning	£ 5,489.00
1.5	Training	£ 5,346.00
1.6	Project Management	£ 16,133.84
Total:		**£ 246,617.29**
Quote 2	**COMPANY 2 (techniques: Vibration & Shock Pulse)**	
2.1	Total Hardware	£ 136,786.83
2.2	Total Software	£ 836.06
2.3	Installation	£ 50,985.00
2.4	Commissioning	£ 4,990.00
2.5	Training	£ 4,860.00
Total:		**£ 198,457.89**
Quote 3	**COMPANY 3 (techniques: Vibration & PeakVue)**	
3.1	Total Hardware and Software	£ 114,592.00
3.2	Installation, Training and Project Management	£ 50,000.00
Total:		**£ 164,592.00**

Table 29: Breakdown of costs to install real-time vibration condition monitoring

5.4 COMPARATIVE ANALYSIS: COST SAVINGS AND OPPORTUNITIES

The previous section established the baseline OPEX, CAPEX and technical feasibility cost positions. This section utilises the information from the previous section to undertake a comparison between the current case maintenance strategy (time-based PPM) and the proposed strategy of incorporating condition-based maintenance using real-time vibration monitoring. The analysis considers the total remaining life of the contract (sixteen years).

5.4.1 OPEX: CURRENT VS. PROPOSED

CURRENT OPEX	PPM	RM	Electricity	Total
Annual (Based on 2014)	£12,628.23	£46,178.43	£409,238.40	£468,045.06
Total over 16 years (2015-2031)	£240,088.87	£877,947.53	£7,780,469.50	£8,898,505.90
NB: 2 per cent per year cost increase factor is used to consider GDP (Gross Domestic Product).				

Table 30: Summary of OPEX over total contract life based on current solution.

PROPOSED OPEX	PPM	RM	ProM	Electricity	Total
Annual (Based 2014)	£1,567.16	£46,178.43	£5,501.26	£409,238.40	£462,485.25
Total over 16 years (2015-2031)	£29,795.00	£854,328.45	£104,590.34	£7,368,327.97	£8,357,041.76
The calculations have been undertaken using the yearly cost factors detailed in Table 33					

Table 31: Summary of OPEX over total contract life based on proposed solution.

PROPOSED OPEX COST INCREASE FACTORS		
	Annual change	**Description**
Reactive Maintenance (RM)	1.688%	2% GDP increase 0.3125% decrease per year (**5% in total**)
PPM (Only 1 x 12Monthly PPM per annum)	2.00%	2% GDP increase per year
Electricity	1.38%	2% GDP increase 0.6250% decrease per year (**10% in total**)
Proactive Maintenance (ProM) (6 x 1Monthly PPM cost)	2.00%	2% GDP increase per year

Table 32: Key cost increase factors used per year.

5.4.2 CAPEX SAVINGS AND OPPORTUNITIES: BEARING REPLACEMENT STRATEGY

Based on historic invoices, it costs in approximately £4,800 to replace the bearings per asset. Therefore to reactively replace all the bearings in scope (pump, fan and motor) it could potentially cost approximately £250,000. The bearings replaced in the last two years highlight:

1. An opportunity for continuous monitoring to reduce risk of unplanned failure whilst increasing operational life.
2. The replaced bearings appear to have failed between 19,000 and 43,000 hours of operation, whilst the bearings in other assets still appear to be operating without failure (continuous monitoring and operating data could explain reasons behind the discrepancies in failure).
3. The need for a central replacement strategy based on age (e.g. 10 years), however not all the bearings will require replacement at a specified age therefore the strategy can be optimised through understanding of the Plantroom environment, asset operating and bearing condition itself using vibration analysis.
4. Based on age alone **all bearings** will be replaced twice during the contract concession period, with all the bearings approaching end of life at the end of the 2032 liability period. However, as shown in Figure 32, if all the bearings are changed once (i.e. in 2016), then another change may not be required for all the bearings as the life can be optimised. Therefore through maximising the life via continuous monitoring and proactive interventions there is a significant opportunity to save in the region of £250,000.

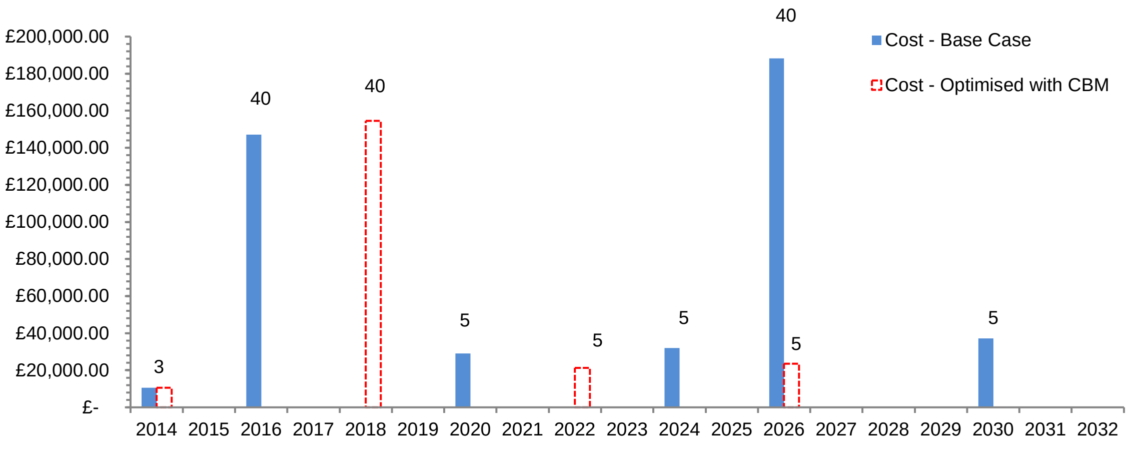


Figure 32: Optimised bearing replacement strategy through CBM

5.4.3 SUMMARY OF FINANCIAL SAVINGS / LOSS

Annual change factor	*+2%*	*-0.3125%*	*-0.6250%*	*+2%*	
	PPM	**RM**	**Electricity**	**ProM**	**Total**
Current	£240,088.87	£877,947.53	£7,780,469.50	£-	£8,898,505.90
Proposed	£29,795.00	£854,328.45	£7,368,327.97	£104,590.34	£8,357,041.76
***%-+** (with GDP)*	*-88%*	*-3%*	*-5%*	-	*-6%*
Saving/Loss	£210,293.87	£23,619.08	£412,141.53	£(104,590.34)	£541,464.14

Table 33: Summary of savings/loss over 16 years.

Quotations for implementing real-time CBM were acquired from three different suppliers. The cost analysis is undertaken based on the cheapest quote (quote number three).

Overall Cost of implementation: The total cost in 16 years will be £205,025.14 (excluding VAT and based initial capital cost and around £2,000 annual support cost (with 2% GDP increase per year). Therefore the average cost of implementation per year will be £12,814.01.

Overall savings opportunity: As shown in Table 34, the estimated OPEX saving is £541,464.14. Additionally the CAPEX savings of £250,000 from optimising bearing replacement provides a total savings opportunity of £791,464.14.

5.4.4 OTHER BENEFITS AND OPPORTUNITIES

Although the following benefits are difficult to quantify they will also be visible and should be considered in the decision making process:

- Better asset condition data to inform Life Cycle decisions.
- Better asset operating and Plantroom condition data to inform maintenance decisions and interventions.
- Whole life extension of each asset (e.g. additional hours of operations).
- Ability to closely monitor damaged bearings and optimise as much as possible to maximise life.
- Improved quality of service through reduction in unplanned downtime.
- Reduction of risk – better risk management relating to unplanned failures.
- Opportunity to reduce risk at hand-back stage through evidencing the condition of assets.

5.5 CONCLUSION AND KEY FINDINGS

This study forms the first strand (and initiation) of the overall research framework (see Section 4.6). The objective of this strand is to analyse the feasibility, costs, benefits and opportunities associated with implementing the proposed CBM based predictive maintenance philosophy within the context of the selected FM case study. The researcher, imbedded within the case study, employed a mixed method approach to collect the necessary datasets, which were then iteratively and collectively scrutinised by the action research platform (EngD board members).

The study firstly analysed the existing OPEX and CAPEX positions. In terms of OPEX, the assets are subject to time-based maintenance (PPM) and RM (if/when necessary). The costs associated with undertaking PPM is calculated to be £12,628.23 per annum, while the RM is contractually fixed at three per cent of the asset value, £46,178.43. Additionally, the annual cost of electricity used by the assets is calculated to be a substantial £409,238.40, which results in the emission of 2,278.8 tonnes of CO_2. With regards to the CAPEX position, the replacements of bearings were identified as the most significant cost. However, detailed analysis of the historic bearing failures and replacements suggests that the hours of life achieved are below the literature and industry recommendations of 50,000 to 100,000 hours of life. Furthermore, the current strategy of reactively changing all the bearings when necessary is estimated to cost £250,000.

Secondly, the study established the feasibility position through consulting three external specialist CBM companies and acquiring quotations to implement real-time vibration monitoring in-line with relevant ISO standards. Using the most economical option, the total cost of implementation is calculated at £205,025.14.

Finally, the potential key impacts of implementing the proposed solution are outlined parallel with literature findings. These impacts are subsequently used to conduct a comparative cost/savings analysis over the sixteen years remaining life of the contract.

Based on the comparative analysis of the most economical feasibility quotation, current expenditure position and the potential key impacts, it is anticipated that the implementation of the proposed CBM solution has the following prospective characteristics:

- Reduce RM by five per cent (through reducing risk of unplanned breakdowns). This would attribute to an estimated saving of £23,619.08.
- The continuous condition monitoring would enable the time-based PPM to be reduced (removing monthly and three monthly planned interventions). This could provide a saving of £210,293.87.

- The efficient, fault free operation of assets is documented to provide energy savings of up to 20 per cent (Rao, 1993; Saidur 2010), therefore, a total ten per cent reduction of electricity can be anticipated over the sixteen years. The savings relating to this is estimated to be in £412,141.53.
- The proposal requires the undertaking of proactive maintenance (when a fault does occur). This is calculated to be an additional cost at £104,590.34.
- Continuous condition monitoring would enable better optimisation of bearing life, therefore instead of replacing bearings reactively, it would be possible to plan the replacements based on condition. This provides a savings opportunity to reduce the total number of bearing replacement and potentially save £250,000.

On balance, the most significant observations outlined in this study are as follows:

- It is technically feasible to implement the proposed solution at a total sixteen-year cost of £205,025.14.
- Implementing the proposed solution is financially justifiable when considered over the life of the PFI contract. There could be a total potential OPEX saving of £541,464.14 and an opportunity to save up to £250,000 CAPEX. Thus providing a 386% net savings opportunity on total cost of implementation.
- The financial savings would be supplemented with the numerous unquantifiable benefits and opportunities, such as the ability to make informed life cycle decisions, improved quality of service through reduced unplanned downtime and better management of risks (particularly at the end of the PFI contract where evidence of asset condition is required).

The fundamental outputs from this strand enabled the researcher to develop the Board of Directors business cases, and secure significant financial investment and approval to implement the proposed solution.

5.6 BOX 5: SUMMARY OF TECHNICAL FEASIBILITY AND COST BENEFIT

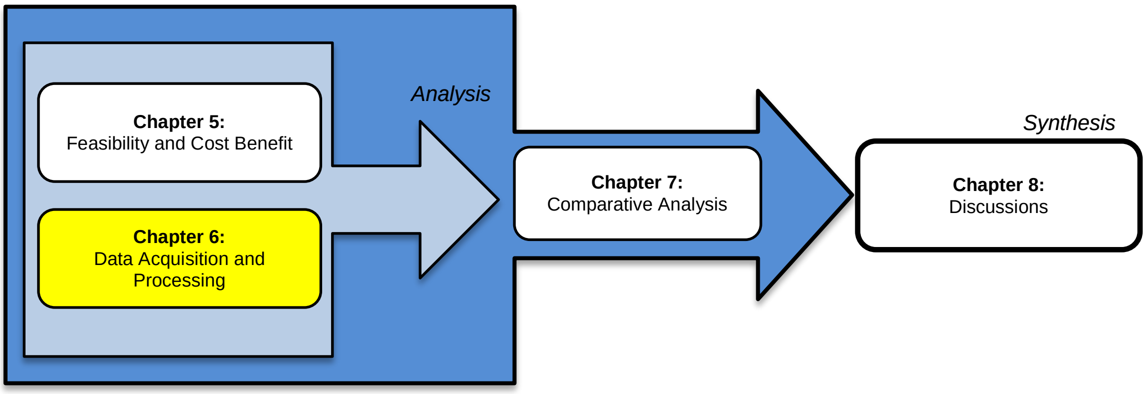
This chapter details the first strand of the overall research framework (technical feasibility and cost benefit analysis), in summary:

- A mixed method approach is implemented on the case study to collect the required data. The methods included:
    - Interviews – conducted through a less formal *'interview guide approach*'.
    - Interrogation of various systems to acquire the relevant event data and historic information relating to the assets.
    - Consultations with specialist external companies to acquire technical guidance and cost information.
- The overall methodology is implemented in conjunction with the action research platform (Monthly EngD Boards) – this ensured collective and iterative scrutiny of the analysis and findings.
- The most economical quotation (out of three) is calculated to be £205,025.14 (over sixteen-years).
- The comparative analysis of the cost findings over the remaining life (sixteen-years), suggests that the implementation of the proposed solution could provide:
    - An OPEX savings opportunity of £541,464.14.
    - A CAPEX savings opportunity of £250,000.
    - Numerous unquantifiable benefits and opportunities relating to risk management and reduction in downtime as well as informed life cycle decision-making.

The next chapter will detail the implementation of the proposed solution and the associated quantitative data acquisition and processing.

6 Data Acquisition and Processing

This is the second analysis chapter. The purpose of this chapter is to describe the methodologies implemented and present the quantitative sensor data collection results in preparation for the final chapter in this part, which will conduct a comparative analysis of the results from both analysis chapters.



This chapter follows a definitive structure which describes *how* the large raw datasets were captured and managed, *what* processing was undertaken and *what* results were acquired. Moreover, where applicable the ethnography observations are included especially relating to key obstacles encountered. Fundamentally, this chapter focuses on the first two elements of the Jardine model for CBM implementation (Jardine et al. 2006) namely, data acquisition and data processing. To simplify the analysis and subsequent synthesis, as well as ensure validity and reliability of the overall study, this chapter is split into three distinct sections:

1. **Plantroom Temperature and Relative Humidity:** The installation of eleven temperature and humidity sensors at close proximity to the assets in scope, the data will be integrated into the BMS and combined with outside temperature and humidity data.
2. **Operational and Energy:** The extraction of operations and energy consumption data from BMS.
3. **Online Vibration Analysis:** The implementation of vibration accelerometers on the assets, the wiring and integration into the Machinery Health Monitoring Software and BMS.

6.1 PLANTROOM TEMPERATURE AND RELATIVE HUMIDITY

Results from this section contribute towards answering the overall research question and more specifically sub-question 1.3 (examined in the next chapter).

6.1.1 DATA ACQUISITION

Prior to the initiation of this research project, it was not possible to acquire the plantroom temperature and relative humidity data for the case building. Therefore, as part of this project, a total of eleven sensors with dual capability were installed in close proximity of the assets in scope.

The Siemens QFA 2020 temperature and humidity sensors was selected as this device had the necessary accreditations and security approvals for installation in the building. Furthermore, the sensor was compatible with the Building Management System (BMS) interface consequently it was possible to hardwire the sensor directly into the BMS network. This enabled data collection to be automated and managed centrally as part of the core buildings operations systems.

In addition to the eleven new sensor data collection, the BMS was also configured to save the temperature and relative humidity outside the building. These two additional points were already being monitored since they were necessary for triggering the HVAC system controls. However, the data was not being stored until it was configured on the BMS to be saved as part of this project.

Therefore, the final sensor setup totalled twenty-four data points consisting of twenty-two internal and two external readings. The data collection intervals were selected to be every five minutes (24 hours a day), this ensured the most realistic position was being reflected by the data.

The collected (raw) data points were automatically saved into a Comma Separated Value (CSV) file and emailed to the researcher every week. The final processing and analysis was conducted on **97,356** rows of data collected over a year (January – December).

To ensure reliability and accuracy of the readings being collected a remote data logger was used to validate the results through an overnight collection conducted on a monthly basis.

6.1.2 PHOTOS OF SETUP: TEMPERATURE AND RELATIVE HUMIDITY

Figure 33: Siemens QFA 2020 temperature and humidity sensor

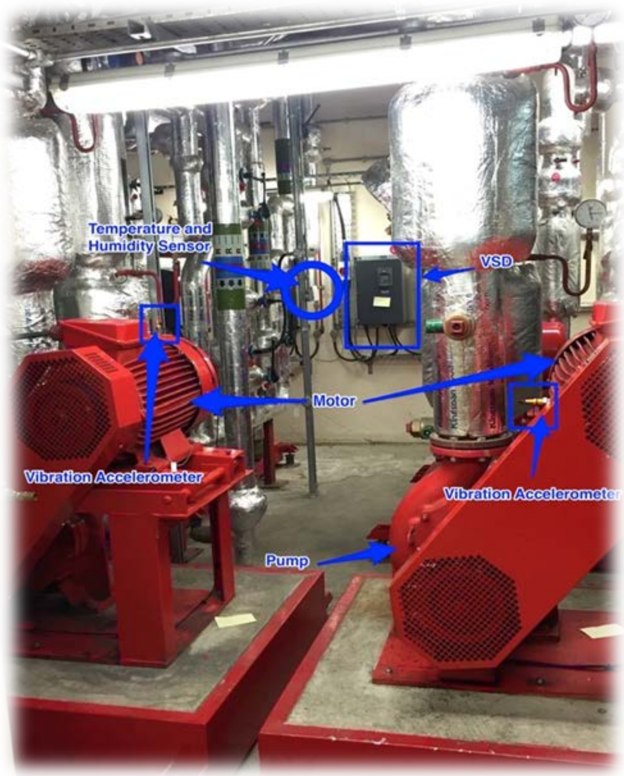


Figure 34: Siemens QFA 2020 temperature and humidity sensor in relation to Vibration Accelerometers and assets.

6.1.3 DATA PROCESSING

The raw temperature and relative humidity data extracted from the BMS required several stages of preparation and processing before any outputs and interpretations could be conducted. Therefore, the researcher implemented several data management and processing protocols such as the stages detailed in Jardine et al., (2006), Rudo (2013) and SKGTechnologies (2010), as shown in Figure 35. An example of the raw data is available in Appendix D:

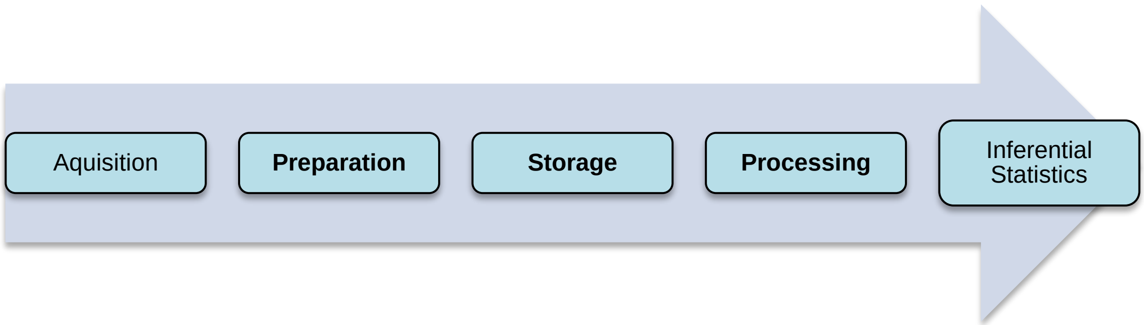


Figure 35: Stages of data processing
Source: Rudo 2013; SKGTechnologies (2010)

Preparation: On a weekly basis, the researcher categorised and coded the extracted data in preparation for storage and processing. The raw data was coded and categorised into twenty-four distinct groups, as shown in Table 35.

Location	**Sensor Description (Temperature)**		**Sensor Description (Relative Humidity)**
9th Floor Roof	AHU 09 (TEMP)		AHU 09 (HUM)
9th Floor Roof	AHU 10 (TEMP)		AHU 10 (HUM)
9th Floor Roof	AHU 17 (TEMP)		AHU 17 (HUM)
9th Floor Roof	AHU 18 (TEMP)		AHU 18 (HUM)
9th Floor Roof	CT 01 & 02 (TEMP)		CT 01 & 02 (HUM)
9th Floor Roof	CT 03 & 04 (TEMP)		CT 03 & 04 (HUM)
9th Floor Roof	CT 05 (TEMP)		CT 05 (HUM)
9th Floor Roof	CT 06 (TEMP)		CT 06 (HUM)
Outside	Outside (TEMP)		Outside (HUM)
Basement level 2	PR A (TEMP)		PR A (HUM)
Basement level 2	PR B (TEMP)		PR B (HUM)
Basement level 2	PR Chiller (TEMP)		PR Chiller (HUM)

Table 34: The 24 coded data points and location details

Storage: To accumulate the large dataset several databases were setup, which were updated with the coded data.

Processing: The final processing of the data firstly involved the application of descriptive statistics and central tendencies, which was necessary preparation for the second phase of applying inferential statistics and extracting outputs and interpretations (see section 7.3).

6.1.4 DESCRIPTIVE RESULTS

The processed results are available in Appendix E and have been visualised in Figures 36 and 37. Using the descriptive statistics methods discussed in 4.7.1 (Research Design), the following observations can be drawn from the results:

Plantroom A (PRA A): The results from this location stand out and are noteworthy:

1. The temperature in this location consistently exceeded 40°C every day and month throughout the year with limited variance.
2. There were numerous instances when the temperature in this location exceeded 50°C. This was predominately between January and March, and also in December.
3. The highest recorded temperature was 56.3°C (8% humidity) recorded on 30th December (between 06:00 and 06:40) during which the outside temperature was 0.5°C (92% humidity).
4. The highest average temperature was recorded in January at 49.65°C (13.1% humidity) and the lowest average in October at 41.20°C (26.7% humidity).
5. The average annual temperature was 46.5°C (19.4% humidity) which is significantly higher than the outside 13.4°C and all other internal locations (closest is Plantroom B at 29.9°C).
6. Reflecting the high temperatures, the lowest average relative humidity was during January at 13.1% and similarly highest during October at 26.7%.

Basement vs. Roof locations: Comparing the three basement locations (plantroom A, B and Chiller) with the eight roof locations the following observation can be made:

1. Throughout the year, the basement locations all appear to be hotter (high temperature) and drier (lower relative humidity).
2. The temperature and relative humidity of roof locations appear to positively fluctuate in conjunction with the outside results. This is somewhat true for the basement locations, except plantroom A results where the temperatures appears to vary negatively with the outside conditions.
3. Analysing the annual averages for the roof locations, CT 01 & 02 location appears to be the coolest (15°C, 66.3%) and the warmest is CT 06 (24.5°C, 38.1%), closely followed by AHU 18 (24.3°C, 36.5%).
4. Out of the three basement locations, the Chiller plantroom appears most similar to the roof locations with annual average of 26.4°C, 33.2%.

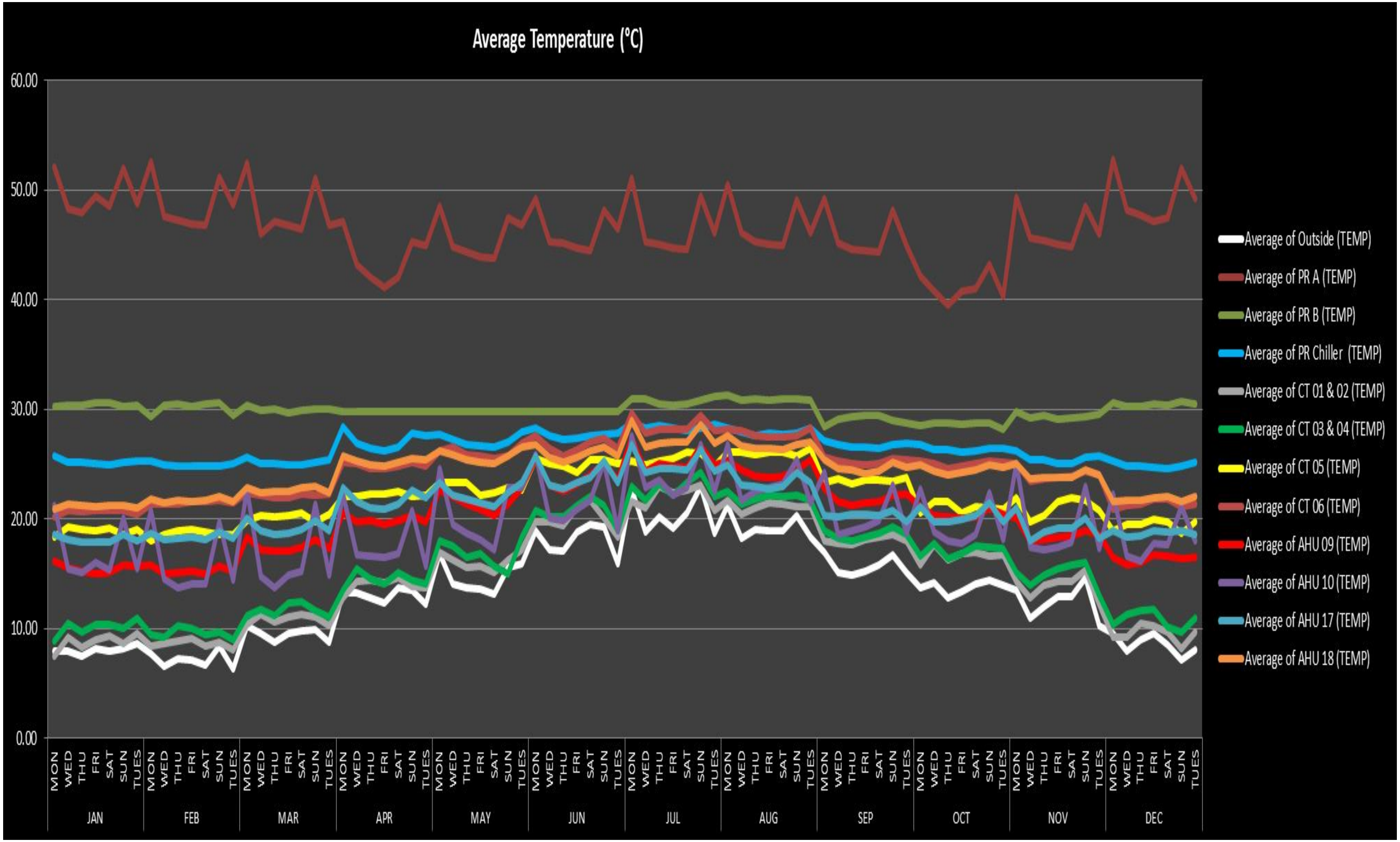


Figure 36: Average plantroom temperatures throughout the year per day and month.

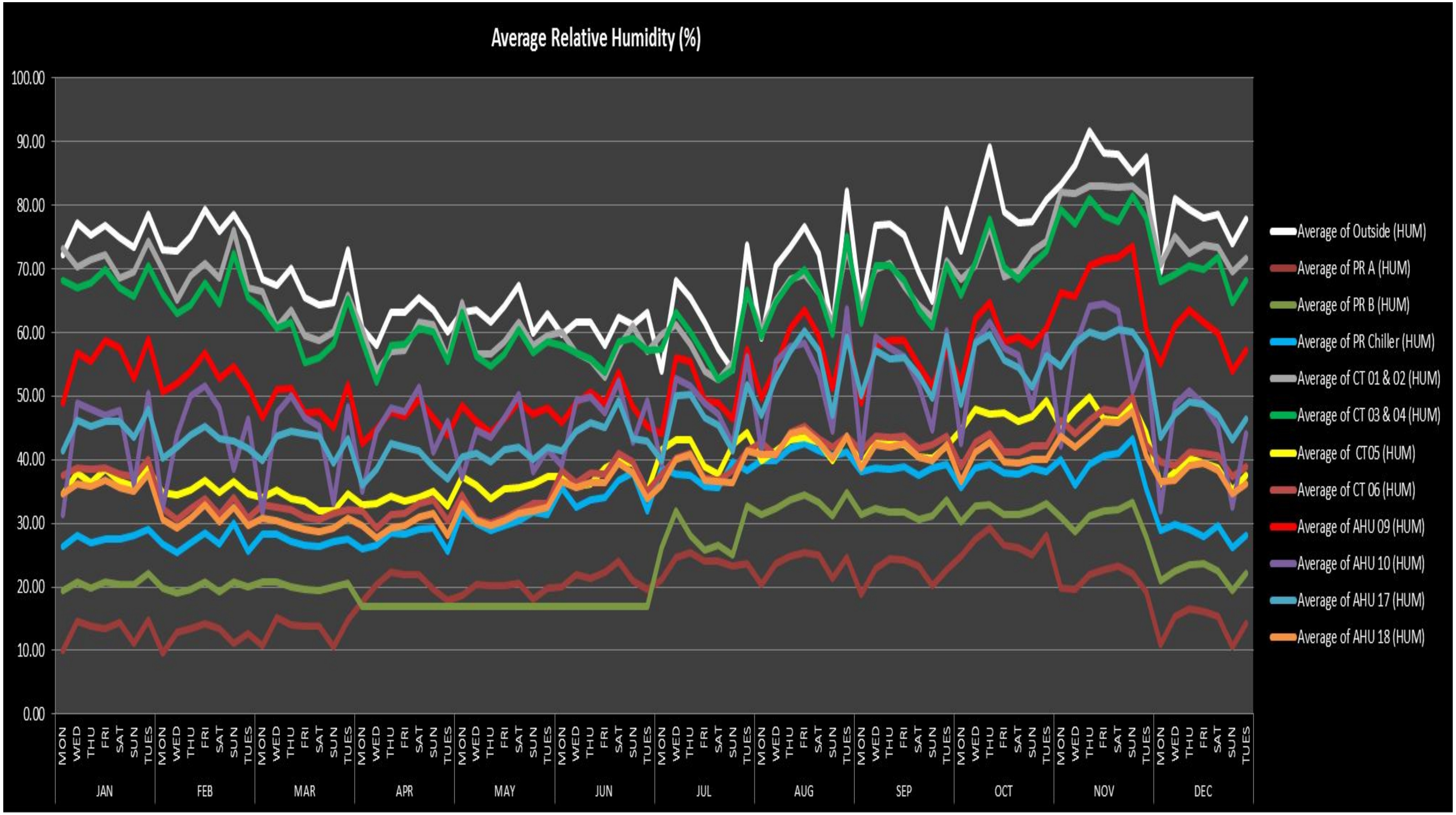


Figure 37: Average plantroom relative humidity throughout the year per day and month.

6.1.5 KEY FINDINGS: PLANTROOM TEMPERATURE AND RELATIVE HUMIDITY

The key findings from this section are:

- **Data acquisition and processing within FM:**
  - The installation and integration of dual sensors into the BMS was straightforward and the existing BMS network infrastructure aided the technical feasibility.
  - Processing the large quantity of collected data requires appropriate methodology, time and expertise.

- **Analysing the processed data, indicates that:**
  - Plantroom conditions typically vary throughout the building.
  - Majority of the condition change appear to mirror and fluctuate with the external conditions.
  - Plantroom A consistently has high temperatures and low relative humidity (annual averages of 46.5°C, 19.4%). Moreover, temperatures in this location exceeded 50°C at numerous occasions between January and March as well as December.
  - Throughout the year the basement locations (Plantrooms A, B and Chiller), all have higher temperatures and lower humidity than the Roof locations.

6.2 OPERATION AND ENERGY

Results from this section contribute towards answering the overall research question and more specifically sub-question 1.3 (examined in the next chapter).

6.2.1 DATA ACQUISITION AND PROCESSING

As detailed in the Research Design chapter (4.6.2), the BMS continuously monitors and controls the asset operation characteristics through the Variable Speed Drives (VSD) that are connected to the assets. The VSD is an electrical system (also known as an inverter) that is used to control AC motor speed through adjusting the frequency that is supplied to the motor. The BMS has the functionality to report numerous operation and energy consumption parameters, such as:

- **Speed*:*** The speed that the asset is operating in Revolutions per minute (RPM).
- **Current:** The current being consumed in Amperes (A).
- **Torque:** The torque of the motor in Newton Metres (Nm)
- **Actual Power:** The actual power used in kWh.
- **Total kWh:** The accumulative electricity used.
- **Reference frequency:** The frequency in Hertz (Hz) relating to the operation.
- **Start/Stop Times:** The starting and stopping times.
- **Fault log/error code indicators:** Logging of faults relating to the VSD and relevant codes.

However, although the functionality is available to acquire such parameters, the VSDs and the BMS were not configured to capture them. Therefore, as part of this project, settings were adjusted on the VSD to send the additional parameter data and the BMS was configured to store the data. Furthermore, reports were setup on the BMS to extract the data on a weekly basis. The data collection intervals were selected to be every five minutes (24 hours a day). The collected (raw) data points were automatically saved into a Comma Separated Value (CSV) file and emailed to the researcher every week.

The raw data was processed using the same methods as the temperature and relative humidity data (Section 6.1.3). The processed data was stored in two databases, Basement and Roof. The final processing and analysis was conducted on **528,697** rows of Roof data and **466,389** rows of basement data, which was collected over a year (January – December). To aid answering the research question, processed data relates to operational assets only.

6.2.2 Photos of Setup: Operation and Energy from VSD

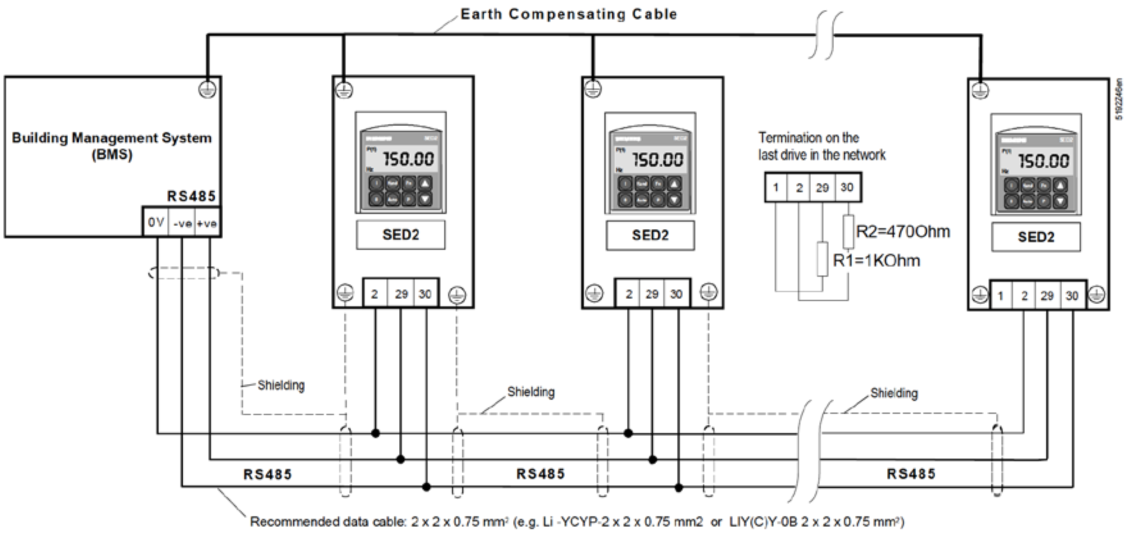


Figure 38: Example of VSD network schematic with BMS

Source: Technologies (2003)

Figure 39: Actual VSD setup network

6.2.3 DESCRIPTIVE RESULTS

Detailed monthly result from the processed data is available in Appendix F and G. The **Summary** for the year is presented in Table 36 (Roof Assets) and Table 37 (Basement Assets).

Summary of operations and energy consumption for Roof Assets (12 months)					
Asset	**N**	**Cum.Current (A)**	**Mean.Current (A)**	**Hours**	**kWh**
AHU10 SF	50,731	1,640,219.49	32.3	4,227.58	93,006.83
AHU09 SF	50,142	2,475,773.55	49.4	4,178.50	91,927.00
AHU10 EF	49,622	1,484,267.40	29.9	4,135.17	76,500.58
AHU18 SF	49,192	1,512,076.10	30.7	4,099.33	75,837.67
AHU09 EF	48,945	1,484,233.60	30.3	4,078.75	75,456.88
AHU17 EF	48,042	1,191,487.30	24.8	4,003.50	60,052.50
AHU18 EF	47,299	1,818,335.69	38.4	3,941.58	59,123.75
AHU17 SF	45,779	1,957,399.15	42.8	3,814.92	83,928.17
CT06 P12	15,399	459,346.95	29.8	1,283.25	38,497.50
CT06 P11	15,264	451,506.90	29.6	1,272.00	38,160.00
CT05 P10	14,505	483,191.40	33.3	1,208.75	36,262.50
CT05 P09	14,441	467,032.20	32.3	1,203.42	36,102.50
CT01 P05	13,480	524,935.00	38.9	1,123.33	41,563.33
CT04 P03	12,950	461,938.40	35.7	1,079.17	39,929.17
CT03 P01	12,618	512,333.60	40.6	1,051.50	38,905.50
CT03 P02	12,276	491,659.85	40.1	1,023.00	37,851.00
CT04 P04	10,849	396,937.55	36.6	904.08	33,451.08
CT01 P06	7,214	317,083.10	44	601.17	22,243.17
CT02 P07	5,542	248,711.15	44.9	461.83	17,087.83
CT02 P08	4,407	191,686.20	43.5	367.25	13,588.25
Sum:	**528,697**	**18,570,155**	**728**	**44,058**	**1,009,475**
N = Number of five minute instances where asset is operational (Current >=1)					

Table 35: Summary of operations and energy consumption of Roof Assets

The 12 month summary results shown in Table 36, indicates that:

- AHU operations and energy can be quantified per Supply Fan (SF) and Extract Fan (EF). Moreover, the data contained the most operational instances relating to AHUs.
- The AHU fans have the highest operational hours, thus highest energy consumption.
- The highest mean current consumption was associated with Pump P07 (40.9 A), while the lowest was AHU 17 EF (24.8 A).
- The two CT06 pumps P11 and P12 have the least number of operational hours, thus lowest consumption.
- All the assets are under the same time-based maintenance regime, yet AHU10 Supply Fan operated 91% more hours than the lowest operating asset CT02 P08.

Summary of operations and energy consumption for Basement Assets (11 Months)					
Asset	**N**	**Cum.Current (A)**	**Mean.Current (A)**	**Hours**	**kWh**
PLA_P01B	48131	1,098,996.50	22.8	4,010.90	74,202.00
CHW_P18	40571	2,620,690.40	64.6	3,380.90	185,950.40
CHW_P24	39023	2,964,388.70	76.0	3,251.90	146,336.30
PLB_P04A	38404	839,067.40	21.8	3,200.30	59,206.20
PLA_P05A	36074	851,544.10	23.6	3,006.20	90,185.00
CHW_P23	35187	2,579,153.60	73.3	2,932.30	131,951.30
CHW_P19	33977	2,329,631.10	68.6	2,831.40	155,727.90
PLA_P05B	29904	747,319.90	25.0	2,492.00	74,760.00
PLB_P01B	29452	298,279.50	10.1	2,454.30	26,997.70
PLB_P01A	22802	271,358.00	11.9	1,900.20	20,901.80
PLA_P01A	22583	746,104.10	33.0	1,881.90	34,815.50
CHW_P02	15460	895,931.00	58.0	1,288.30	70,858.30
PLB_P04B	13732	444,485.90	32.4	1,144.30	21,170.20
CHW_P03	11964	472,228.40	39.5	997	54,835.00
CHW_P01	11331	630,339.40	55.6	944.3	51,933.80
CHW_P09	9944	179,129.90	18.0	828.7	15,330.30
CHW_P11	9705	339,442.00	35.0	808.8	29,923.80
CHW_P08	9166	162,042.90	17.7	763.8	14,130.90
CHW_P10	8979	319,998.50	35.6	748.3	27,685.30
Sum:	**466,389.00**	**18,790,131.25**	**722.5**	**38,865.75**	**1,286,901.42**
N = Number of five minute instances where asset is operational (Current >=1)					

Table 36: Summary of operations and energy consumption of Basement Assets

The 11 month summary results for the basement assets, shown in Table 37, indicates that:

- Pump P01B in Plantroom A operated the most number of hours, closely followed by Pumps P18 and P24 in the Chiller Plantroom.
- Although P18 did not have the highest number of operating hours, it did consume the most amount of energy, and was closely followed by its standby P19.
- The 50:50 duty/standby ratio setups on the BMS scheduling should ensure same number of operating hours, yet P19 operated 549.5 hours less (-16%) than P18. Similarly, P24 operated 319.6 hours (10%) more than its standby P23.
- The highest mean current consumption was associated with P24.
- Although the assets are under the same PPM regime, P01B operated 81% more hours than the lowest operating asset P10 in the Chiller Plantroom.

6.2.4 KEY OBSTACLES

Acquiring data relating to the assets operations and energy consumption did not require any additional hardware to be installed since the capabilities were available through the BMS software configurations. Nevertheless, three major difficulties with the data acquisition and processing were encountered:

1. **Incompatible VSD:** Five of the assets in scope were controlled with an older and uncommon model of VSD that did not have the required network protocol (P1) to interface with the BMS and provide the necessary data. Therefore it was not possible to acquire data for the assets listed in Table 38. All five assets were in the Chiller Plantroom and were substantially larger than the other assets in scope. This did not affect the installation of vibration accelerometers and the subsequent online vibration analysis.

	Assets		kW
1	Primary Condenser Water Pump	P20	132
2	Primary Condenser Water Pump	P21	132
3	Primary Condenser Water Pump	P22	132
4	Secondary Chilled Water Pump	P04	160
5	Secondary Chilled Water Pump	P05	160

Table 37: Asset with no actual operations or energy data

2. **Network limitations:** The IT network infrastructure within the building was aging and volatile. This resulted in several instances of downtime throughout the period of data collection, consequently there were weeks where data collection was not possible. For example, with the Basement assets there was no data available for the whole of September.

3. **Large dataset management:** The processing, management and storage of data points from the VSD was difficult due to the size of the total dataset. For example, as stated in section 6.2.1, the asset operations and energy consumption results were extracted from the total processing of 995,086 rows of data, but each asset had eight data points thus giving a <u>total dataset size of nearly eight million data points</u> (7,960,688). This number excludes the temperature, relative humidity and vibration datasets.

6.2.5 KEY FINDINGS: OPERATION AND ENERGY

The key findings from this section are:

- **Data acquisition and processing within FM:**
  - A variety of data points relating to operations and energy consumption are available and accessible for building assets through the existing BMS network.
  - The data can be easily extracted from the VSD via the BMS without additional hardware installation. However, older models of VSD that are uncommon nowadays do not have the necessary P1 network protocol therefore cannot provide the mentioned data to be obtained via the BMS.
  - Furthermore, limitations relating to a volatile building IT network infrastructure can reduce data collection capabilities, since downtime can result in no data being collected.
  - Processing the large quantity of collected data requires appropriate cloud based data management methodologies, time and expertise.

- **Analysing the processed data, indicates that:**
  - Although the assets are under the same time-based PPM regime, the operations vary significantly. For example, out of the Roof location assets the highest operating asset was 91% more hours than the lowest, while in the Basement location the difference was 81%.
  - Out of the Roof dataset, the AHU Fans were the most operated assets and thus consumed the most energy, while in the basement the highest operations were associated with pump P01B in Plantroom A.
  - The highest energy consumption in the basement was attributed to pumps P18 and P24 in the Chiller Plantroom. P24 also had the highest mean current consumption at 76 Amps.
  - The programmed 50:50 scheduled operations can vary between 10-16%.

6.3 REAL-TIME VIBRATION ANALYSIS

Results from this section contribute towards answering the overall research question and more specifically sub-question 1.2 (examined in the next chapter).

6.3.1 DATA ACQUISITION

The two months installation and configuration phase of the project involved the installation of relevant online vibration data collection instruments. The hardware and software used for the implementation were in-line with the scope of works quotations detailed in Chapter five (detailing the technical feasibility establishment process). Furthermore, the implementation of the instruments was undertaken based on the guidance provided in the relevant international standards, and included the following characteristics and tools:

6.3.1.1 Project Team

A dedicated project team was setup, with regular meetings and site/asset walk-round surveys. The people involved in the project team consisted of site maintenance engineers, specialist consultants (provided by the solution company), selected management staff. The researcher acted as the Project Manager with accountability to the EngD Board. This also provided the opportunity for the researcher to act as an independent observer.

6.3.1.2 Pre-work Procedures

Before initiation, the researcher carried out relevant mandatory pre-work procedures including site risk assessments, development of the method statements and asbestos management plan surveys. These were undertaken in conjunction with qualified specialists and subsequently verified and approved by relevant on site authorities.

6.3.1.3 Measuring Points

In accordance with ISO 13373-1:2002, measurements points most relevant for the assets in scope were established to be vertical and horizontal. Furthermore, the accelerometer installations were mounted as close as possible to the bearings (ISO, 2005). Therefore, on majority of the assets a total of four accelerometers were installed:

1. *Motor Non-Drive End (NDE)*
2. *Motor Drive End (DE)*
3. *Pump/Fan DE*
4. *Pump/Fan NDE*

Five of the assets are direct drive, in these instances only two accelerometers were required (Motor NDE and DE).

6.3.1.4 Accelerometers and Online Units

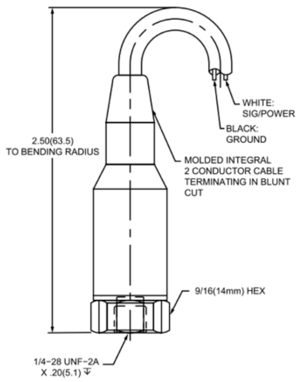
A total of **166** *Emerson A0322LC Industrial Accelerometers* were installed and wired back to the relevant CSI 6500 data collection and monitoring units on the wall. A total of ten wall units were installed within close proximity of the assets, the units were designed to accommodate either twelve or twenty-four inputs, therefore it was necessary to setup four Local Area Networks (LAN) to enable real-time data collection and processing (see section 6.3.1.7).

The selected accelerometers had the following key characteristics:

1. Easy of integration with CSI 6500 Machinery Health Monitoring (MHM) software.
2. Frequency range complies with ISO 13373-1 (0.50 to 10kHz).
3. Limited sensitivity depreciation in higher temperatures.
4. Three point calibration undertaken on the accelerometers and certificates provided (see Appendix H for example of certificate).
5. Mounting studs included.

Figure 40 provides detailed technical specification of the A0322LC accelerometers.

DYNAMIC PERFORMANCE	
Sensitivity (±10%)	100 mV/g
Measurement Range	±50 g
Frequency Range (±3 dB)	0.50 to 10,000 Hz (30 to 600,000 cpm)
Mounted Resonant Frequency	22 kHz nominal
Amplitude Linearity	±1% (0 based, least squares, straight line method)
Transverse Sensitivity	≤7%
ENVIRONMENTAL	
Shock Limit	5000 g pk
Temperature Range	-54 to 121°C (-65 to 250°F)
Temperature Response	See Graph
Sealing / Rating	Molded / IP68
ELECTRICAL	
Settling Time	≤2.0 sec (within 1% of bias)
Discharge Time Constant	≥0.3 sec
Excitation Voltage/Current	18 to 24 VDC / 2.0 to 20 mA
Output Bias	8 to 12 VDC
Output Impedance	<150 ohms
Broadband Resolution (1 to 10 KHz)	350 µg (electrical noise)
Case Isolation	>10^8 ohms
MECHANICAL	
Weight	99.3 grams (3.5 oz) Sensor & Stud Only
Mounting Stud/Torque	¼-28 UNF-2B / 2.7 to 6.8 Nm (2 to 5 lb ft)
Sensor Element/Geometry	Ceramic/Shear
Case Material	Stainless Steel
Connector Type (Top)	Molded Integral Cable (See Versions)
SUPPLIED ACCESSORIES	
Three Point Calibration	
¼-28 Mounting Stud	
VERSIONS	
1. A0322LC	Yellow 3 m (10') Cable
2. A0322LC-1	Yellow 9 m (30') Cable
3. A0322LC-2	Yellow 15 m (50') Cable
4. A0322LC-1-EX	Yellow, Armored, 9 m (30') Cable, Hazardous Area Approved



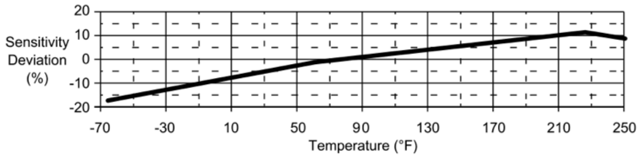


Figure 40: Emerson A0322LC accelerometer specifications

Source: (Emerson) 2013))

6.3.1.5 Key Obstacles

There were two notable obstacles encountered during the installation and configuration:

1. Variable Speed Assets: As discussed in the literature (Chapter 3), the speed at which the asset operates is required to be known or captured since it is an essential component of undertaking vibration data analysis. Out of the 44 assets in scope, half are fixed speed (i.e. only operate at known speed), which can be captured from the BMS and input into the vibration analysis software. However, the other 22 assets (encompassing 82 accelerometers) are variable speed, which means capturing the speed at a given time point is challenging since the speed can vary depending on the buildings HVAC requirements and BMS configurations. Therefore, in addition to the online vibration monitoring hardware procured (CSI 6500), it was necessary to acquire converters that would take input from the VSD and provide output speed to the CSI 6500 units. Figure 41, shows an overview of the final setup.

2. Collecting data only when asset is operating: Due to the duty standby setup proximity and the sensitivity of the accelerometer, there would be continuous vibration data be recorded by the accelerometer which was not related to the asset itself. This would essentially result in large quantities of unreliable data being collected and stored. To prevent this, the VSDs were all connected to the 6500 units through an on/off relay. This enabled vibration data to be collected only when the asset was operational. Figure 41, shows an overview of the final setup.

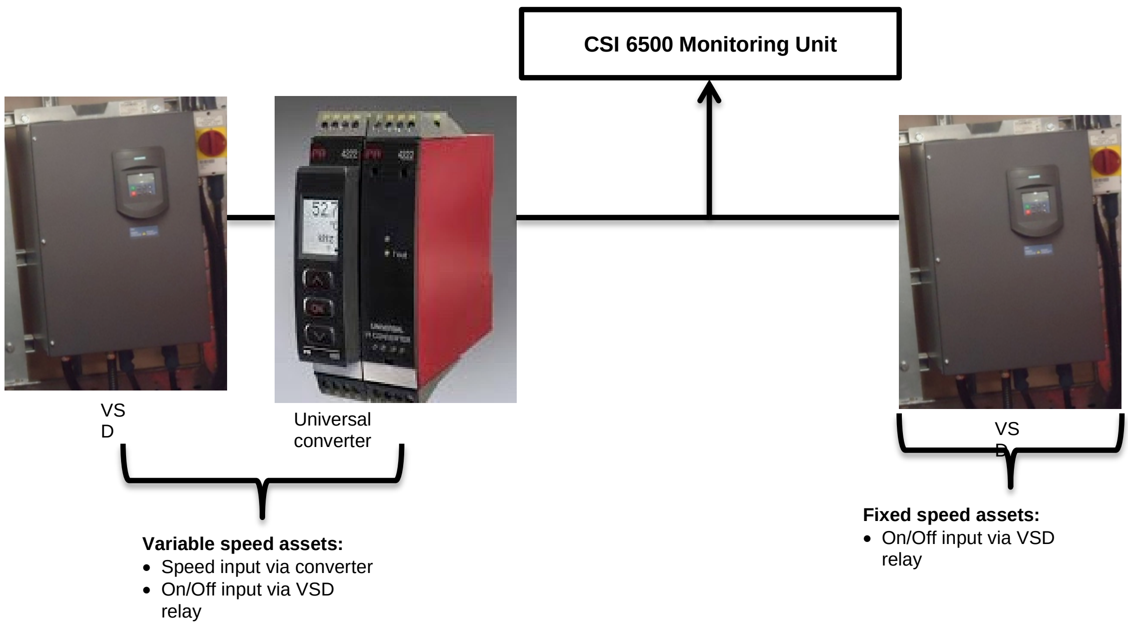


Figure 41: Speed converter and On/Off relay setup

6.3.1.6 Software

CSI 6500 Machinery Health Monitoring (MHM) software for online vibration monitoring was installed on the servers to aid the collection, processing and analysis of the data. Specialist technical consultants undertook the initial setup and commissioning of the CSI 6500 units and MHM software. The solution utilised vibration analysis for key detectable faults discussed in the literature (e.g. misalignment, looseness, unbalance). Additionally, it was inclusive of the most recent version of PeakVue analysis for the detection and diagnosis of bearing faults using high frequency (1kHz to 10kHz).

6.3.1.7 Network Overview

The final online vibration monitoring configuration network for data acquisition consisted of the following:

- 166 Accelerometers
- 10 CSI 6500 Units (wall units)
- 4 Local Area Networks (LAN) with 3 Severs hosting MHM software
- 22 Universal Converters (tachometers)
- 44 VSD Input/ Output (I/O) connections
- MODBUS Gateway data integration with the existing BMS Server (PXC36 controllers).

Example of two networks and illustrated in:

- **Figure 42:** Plantroom B and Chiller – this shows how four CSI 6500 units (Cabinet 2-5) have been networked across two distinct basement locations using Netgear routers and integrated with the MHM software as well as the BMS.
- **Figure 43:** This illustrates the mechanism used to connect Cabinet 8 (collecting data for pumps relating to CT05 and CT06) and Cabinet 10 (collecting data for AHU17 and AHU18 fans) have been integrated into the buildings motor control center (MCC) panel on the roof of the building.

These are further expanded with illustrations of the technical wiring schematics:

- **Figure 44:** Illustrates how each accelerometer and the associated input/output (on/off) relays for Plantroom B have been integrated with the CSI 6500 unit, overall network and the PXC36 connection to the BMS Server.
- **Figure 45:** Shows how each accelerometer and the associated input/output (on/off) relays for AHU17 and AHU18 have been integrated with the CSI 6500 unit, overall network and the PXC36 connection to the BMS Server.

6.3.1.8 Network: Plantroom B and Chiller

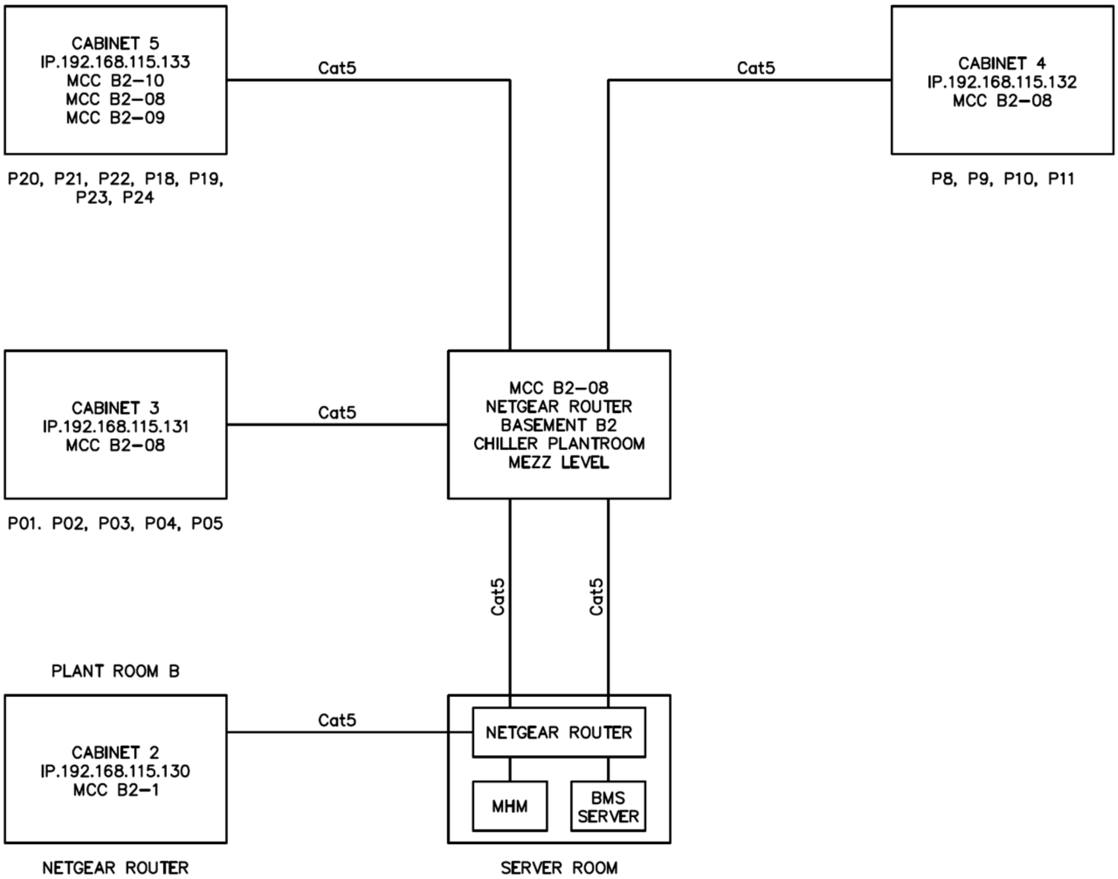


Figure 42: Network diagram of Plantroom B and Chiller

Source: SSE Enterprise drawings

6.3.1.9 Network: AHU 17, AHU 18 AND CT 05, CT06

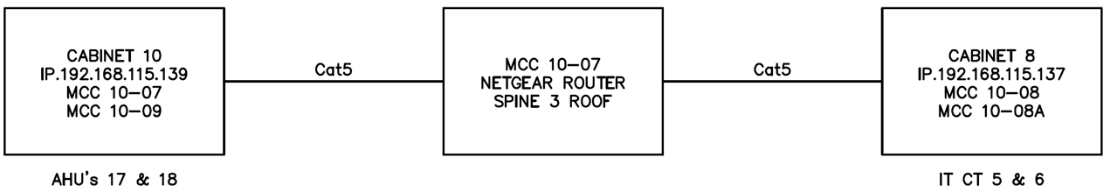


Figure 43: Network diagram of AHU 17, AHU 18 and CT 05 and CT 06

Source: SSE Enterprise drawings.

6.3.1.10 Detailed Installation Schematic

The installation schematics provide an overview of detailed wiring setup and configurations.

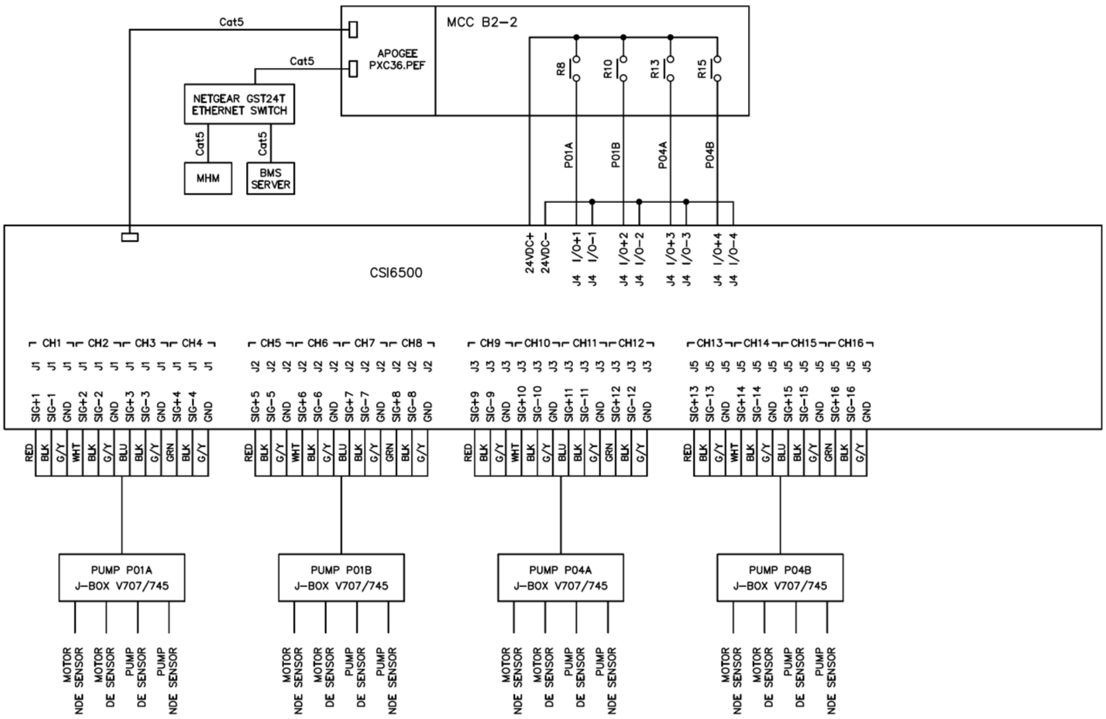


Figure 44: Schematic of Plantroom B: 4 Pumps

Source: SSE Enterprise drawings

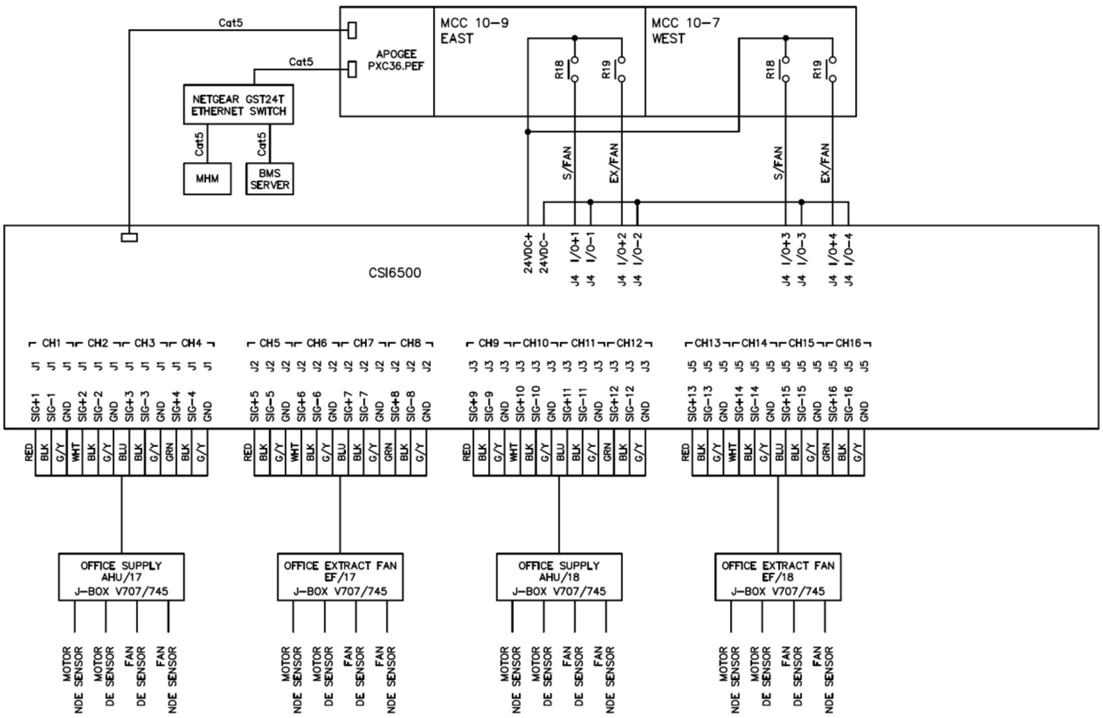


Figure 45: Schematic of AHU 17 and AHU 18: 4 Fans

Source: SSE Enterprise drawings

6.3.2 PHOTOS OF SETUP: REAL-TIME VIBRATION ANALYSIS

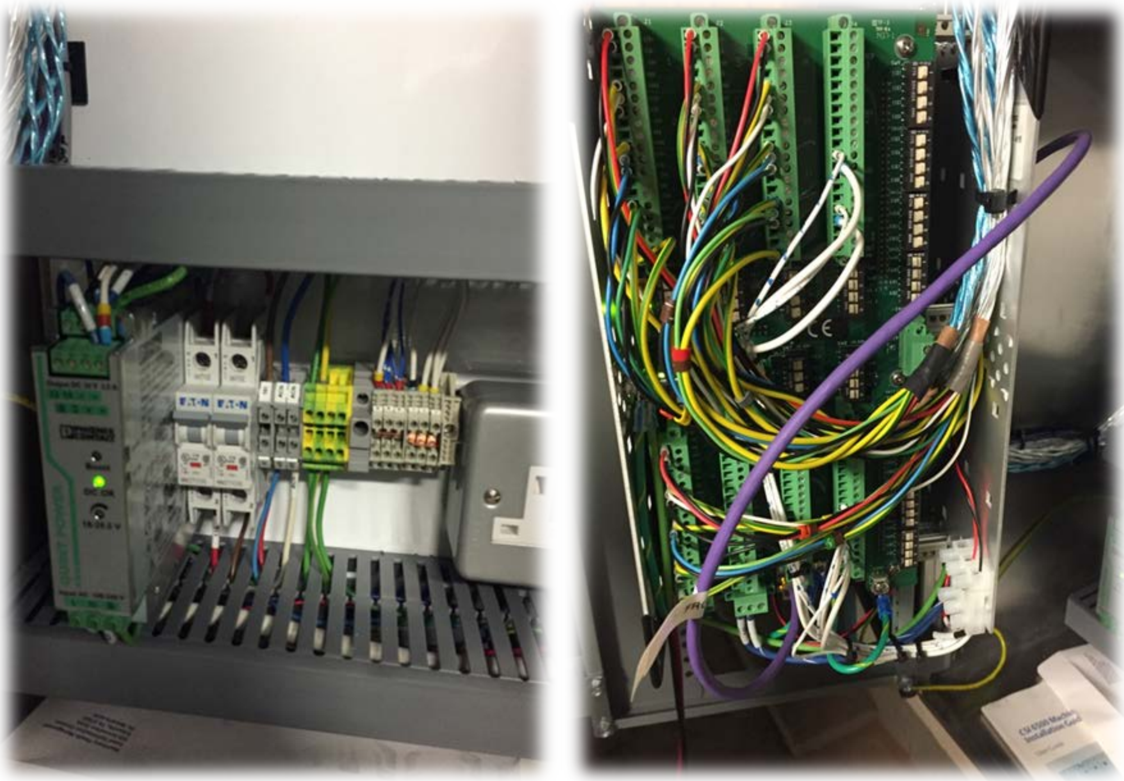


Figure 46: Inside of CSI 6500 units and wiring

Figure 47: Accelerometer on Motor NDE

Figure 48: Accelerometers on Motor and CSI 6500 on wall

Figure 49: Pump duty/standby setup with accelerometer wiring junction box

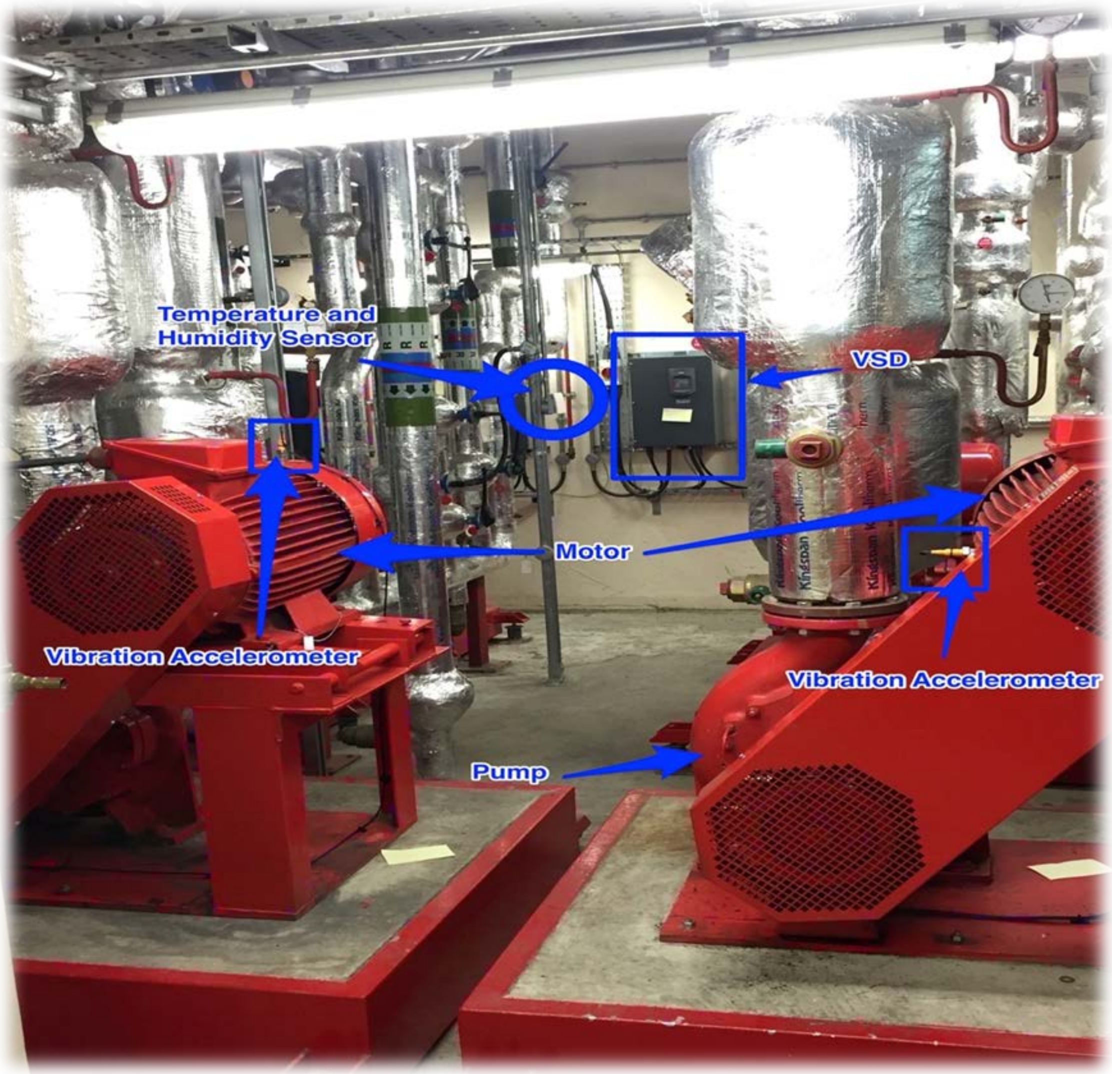


Figure 50: Assets, sensors and accelerometer setup

6.3.3 DATA PROCESSING AND RESULTS

The raw vibration data capture via the MHM software and processed through the appropriate signal processing algorithms built into the software. The validation and verification of data capture was conducted as part of the initial commissioning by qualified consultants. Subsequent data capture was automated (real-time) and the researcher conducted the data analysis (supported by the BINDT certification, as discussed in Research Design), additionally the data analysis was validated by the specialist consult through a monthly site visit. Total of eight months (July - February) of vibration data was analysed as part of this project.

6.3.3.1 MHM Data Processing

The online solution has been configured to process and present the sampled data in a variety of methods and frequency ranges in accordance the best practice ISO threshold. Table 31 shows the processing undertaken per accelerometer.

Over an eight-month period (July-February), the whole online vibration project evidently generated an extremely large and complex continuous dataset that is too exhaustive to include in detail within this section. Therefore the results presented within this thesis have been streamlined to enabling final data synthesis and answering of the original research questions.

Moreover, to fulfil the purpose of this section and demonstrate the complex data, the datasets from one asset (four accelerometers) is visually presented in detail and comparisons made where applicable to others. Additionally, a summary is provided indicating the overall condition of all the assets based on detailed vibration data analysis.

#	Frequency Bands	Frequency Range	Units	Explanation / Faults detection
1	Overall Velocity	0.15 - 80xRPM	mm/sec	General Vibration Severity
2	1xRPM	0.15 - 1.5xRPM	mm/sec	Unbalance
3	2xRPM	1.5 - 2.5xRPM	mm/sec	Misalignment / Twice Electrical Frequency
4	3-8XRPM	2.5 - 8.5xRPM	mm/sec	Looseness Harmonics / Blade/ Vane Pass Range
5	9-35xRPM	9.5 - 35.5xRPM	mm/sec	Mid Velocity Range Bearing Frequency harmonics / Cavitation
6	36-80xRPM	35.5 - 80xRPM	mm/sec	High Velocity Range Bearing Frequency harmonics / Cavitation / common motor slot / rotor bar Frequencies
7	HFD (High Frequency Detection)	1kHz to 20kHz Or 5kHz to 20kHz	G's	Early detection of high frequency energy, such from inadequate lubrication, early/mid/late stage bearing defects.
8	Waveform Pk-Pk	N/A	G's	Mid to late stage impact related fault detection such as bearing faults and rotating looseness faults
9	Crest Factor	N/A	(unitless)	Spikiness of signal (ratio of Pk / RMS) which is used to detect things such as sharp impacts from bearing elements including cage, transient events
10	Overall PeakVue	1kHz High Pass Filter passes all frequencies below this and measures high frequencies from 1kHz to full response range of the accelerometer (PeakVue upper response range is 80kHz and it samples at over 104,500 samples/ per second)	G’s	See below, but not as sensitive as the PeakVue Waveform Pk-Pk
11	PeakVue Waveform Pk-Pk	N/A	G's	Pk to Pk of PeakVue time waveform which is extremely sensitivity (often can be 10x higher than the amplitude of the overall PeakVue overall value) useful for detection of high frequency stress / shock wave detection from lack of lubrication, increased friction between rolling element due to increased loading, very early detection of bearing defects developing beneath the surface of the bearing and of course mid/late stage failure.

Table 38: Processing conducted by MHM for each accelerometer.

6.3.4 RESULTS

6.3.4.1 Summary of Results: Overall Asset Condition (Vibration Analysis)

LOCATION		Condition / quantity at February		
Description 1	**Description 2**	**Red**	**Amber**	**Green**
Basement Level 2	Plantroom A	0	1	3
Basement Level 2	Plantroom B	0	0	4
Basement Level 2	Plantroom Chiller	1	2	13
9th Floor Roof	09 - Plant Area - 092W	0	0	4
9th Floor Roof	09 - Plant Area - 092E	0	0	8
9th Floor Roof	09 - Plant Area - 093W	0	0	8
		1	*3*	*40*
		2.3%	*6.8%*	*90.9%*

Table 39: Summary of asset condition results by location (against ISO Standard)

The result indicates the using online vibration monitoring and analysis it was possible to establish the health conditions of the assets over the eight-month period in-line with the ISO Standards thresholds. The ISO health condition scale is divided into three zones:

- Green = Good operating condition.
- Amber = Reduced operating condition.
- Red = Bad operating condition.

Majority (90.9%) of the assets in scope have a good operating condition, i.e. the vibration levels detected and analysed from all associated accelerometers are within the ISO thresholds and do not relate to any particular fault.

However, although all the assets continued to receive time-based PPM actions, the vibration levels of a minority of assets (9%) were detected to be outside the thresholds and diagnosed to have generated as a result of a fault being present on the asset. Within the latter minority group, three assets were diagnosed to have a fault present and operating at reduced capacity and one at the red threshold to be in bad operating condition.

The one 'bad operating condition' asset relates to pump P24 in the Chiller Plantroom. The fault was initially identified at the beginning of the vibration data collection (July) and categorised to be in the 'reduced operating condition'. The vibration results for this asset is visualised and analysed further in the next section.

6.3.4.2 Detailed Results: Pump 24 (Chiller Plantroom)

This section will illustrate the vibration accelerometer results for **Primary IT Condenser Water Pump P24** (45kW, belt driven) in the Chiller Plantroom.

6.3.4.2.1 Motor NDE: Velocity Fault Frequencies

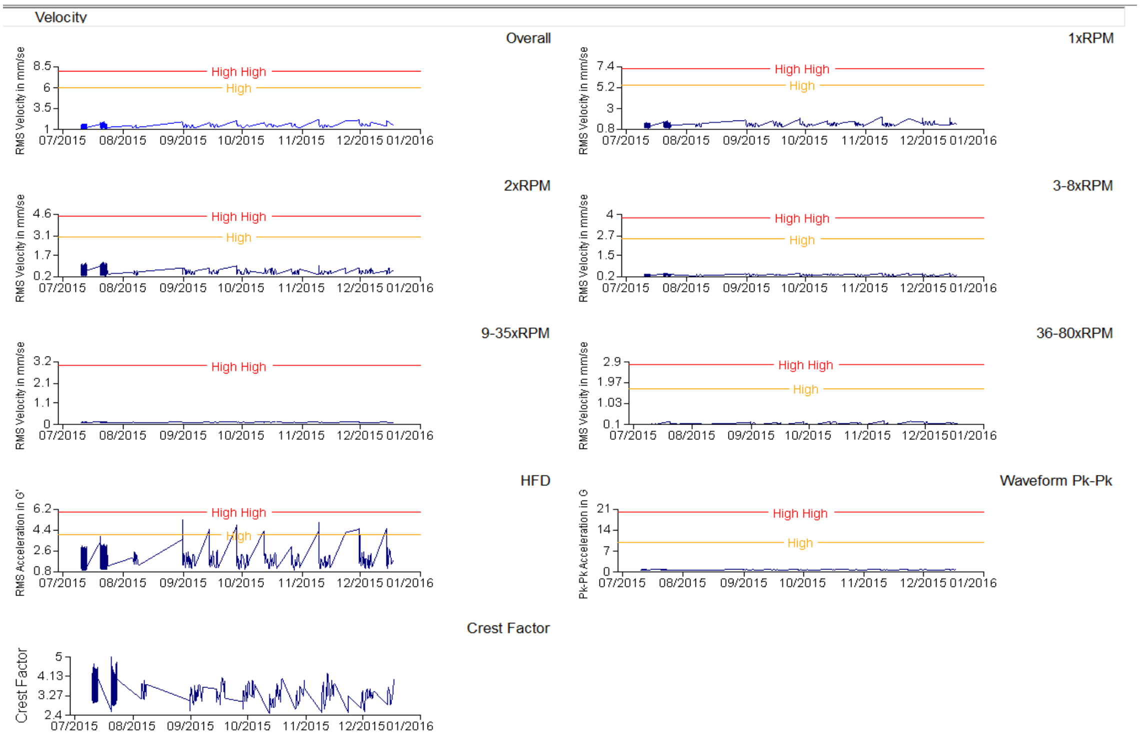


Figure 51: Motor NDE velocity fault frequencies

Figure 51, illustrates that:

- The key velocity frequency bands to be within tolerance.
- The overall velocity trend and the waveform Pk-Pk trends are also within tolerance.
- The High Frequency Detection 1kHz to 20kHz (HFD) trend does reach the ‘amber’ limit, however this is appears to be a stable issue at machine starting up, therefore not a sign of condition deterioration or fault presence. The crest factor appears to mirror this start-up pattern.
- There are no faults present on the Motor NDE of this pump.

6.3.4.2.2 Motor NDE: PeakVue and Velocity Spectrums and Time Waveforms

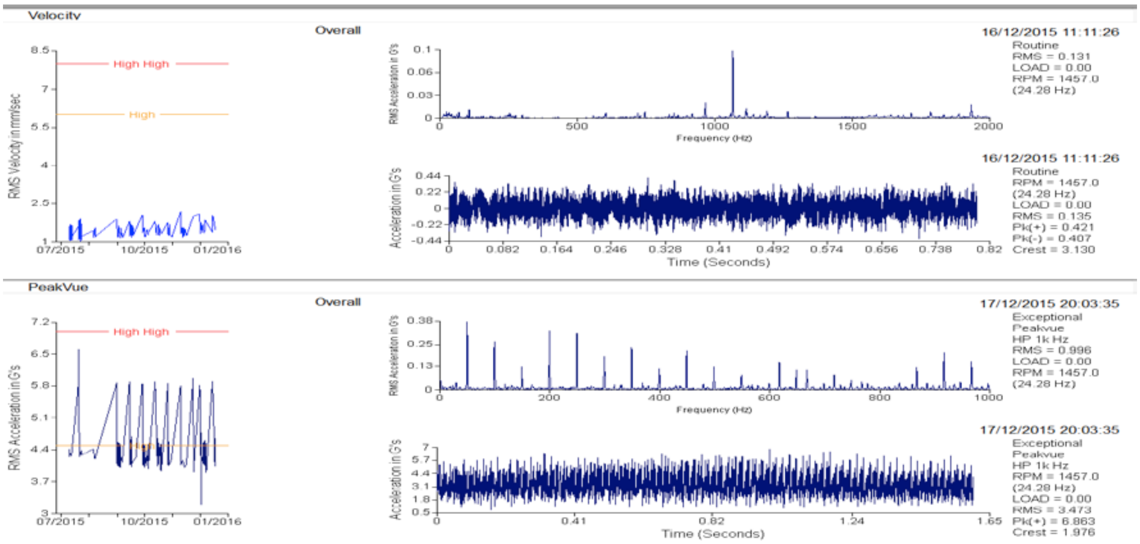


Figure 52: Motor NDE overall velocity and PeakVue

Figure 52, illustrates the healthy overall Velocity and PeakVue trends. It also shows the recent velocity time waveform and spectrum, as well as the PeakVue time waveform and spectrum. Figure 53, further confirms the health condition, it displays two velocity time waveforms and associated spectrums captured eight days apart with very little change.

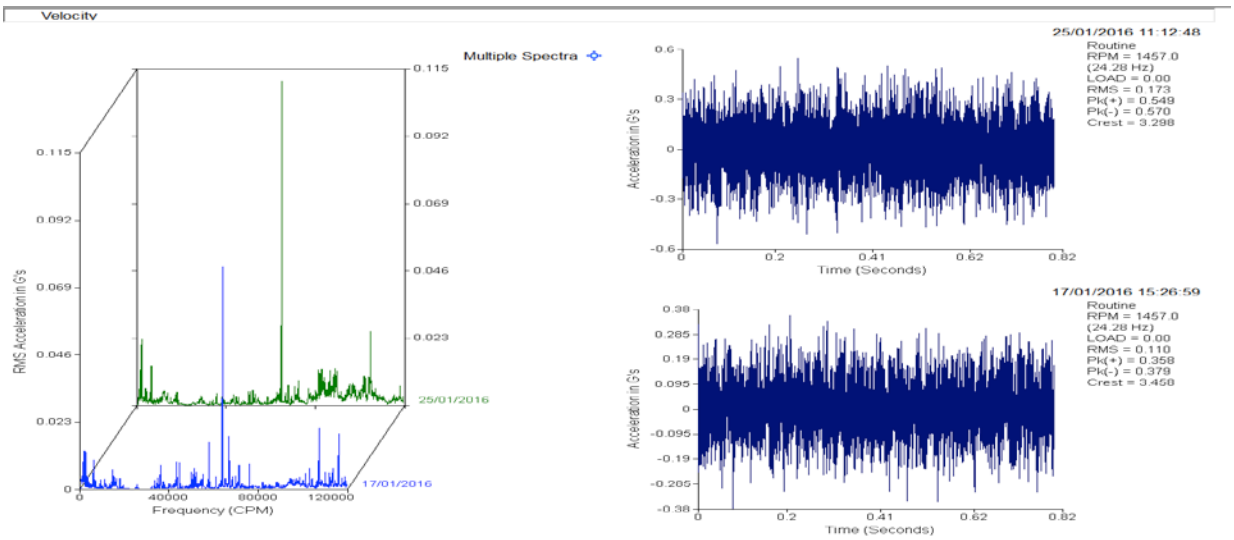


Figure 53: Motor NDE spectrum and time waveform

6.3.4.2.3 Motor DE: Velocity Fault Frequencies

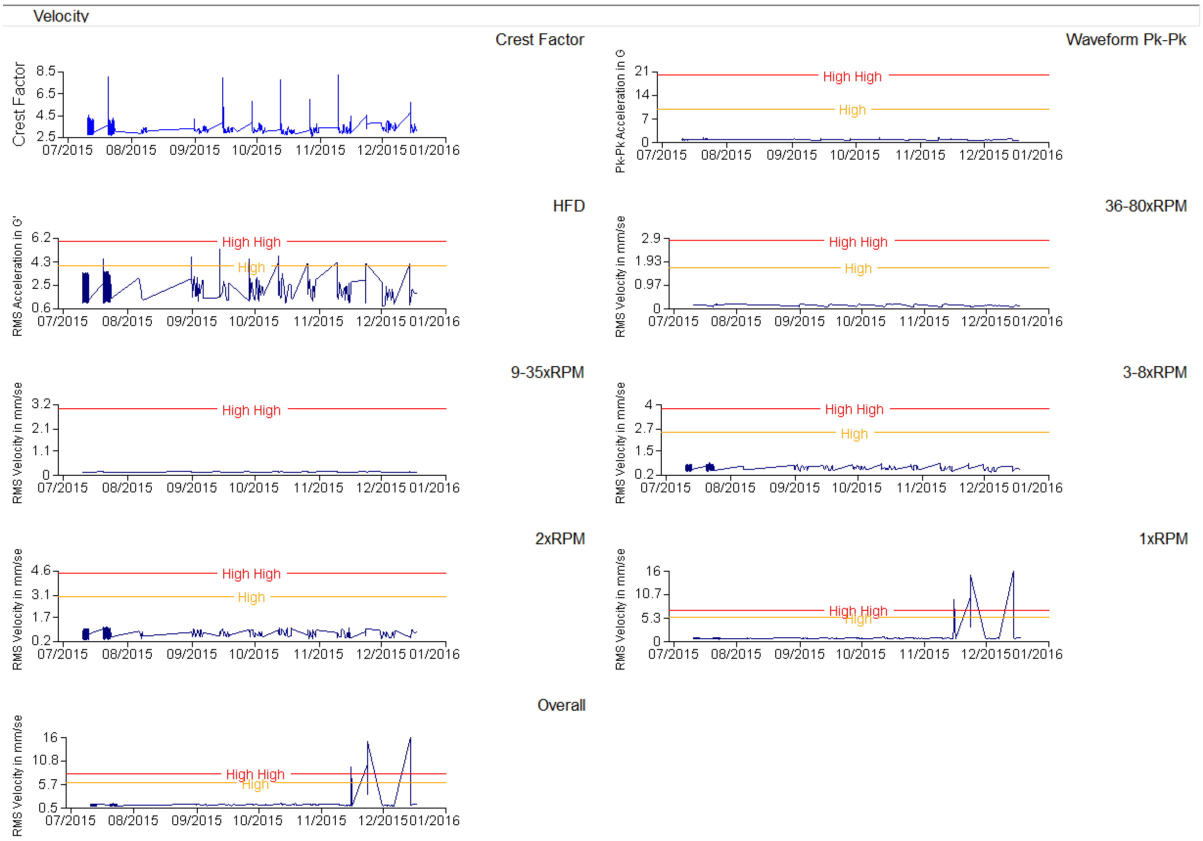


Figure 54: Motor DE velocity fault frequencies

Figure 54, illustrates that:

- The HFD and crest factor same as Motor NDE.
- The overall velocity trending is stable until end of Nov when it increases and exceeds the thresholds. Analysing the 1XRPM data indicates the reason relates to the motor running at or near its critical speed; all other frequency bands are within tolerance.
- Issue with balancing resolved upon detection.

6.3.4.2.4 Motor DE: PeakVue and Velocity Spectrums and Time Waveforms

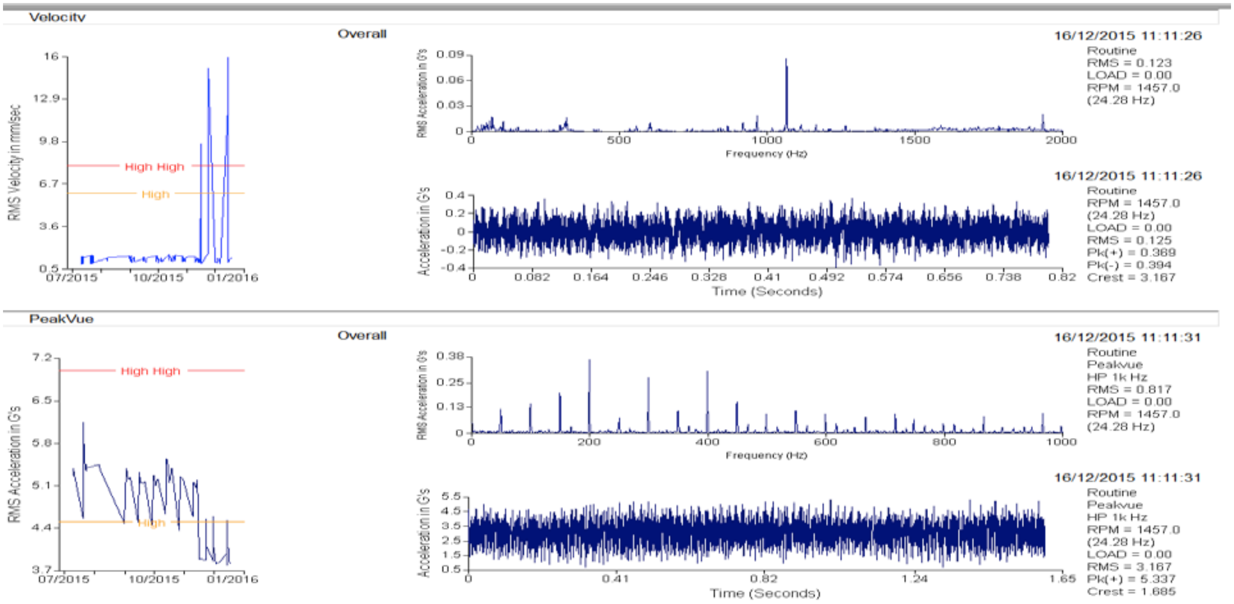


Figure 55: Motor DE overall velocity and PeakVue

Figure 55 shows the overall velocity and PeakVue trends. The high overall spikes are caused by the speeding up and down of the pump controlled by the VSD, which is injecting noise into the accelerometer as it speeds up. Figure 56, shows healthy spectrum and time waveform.

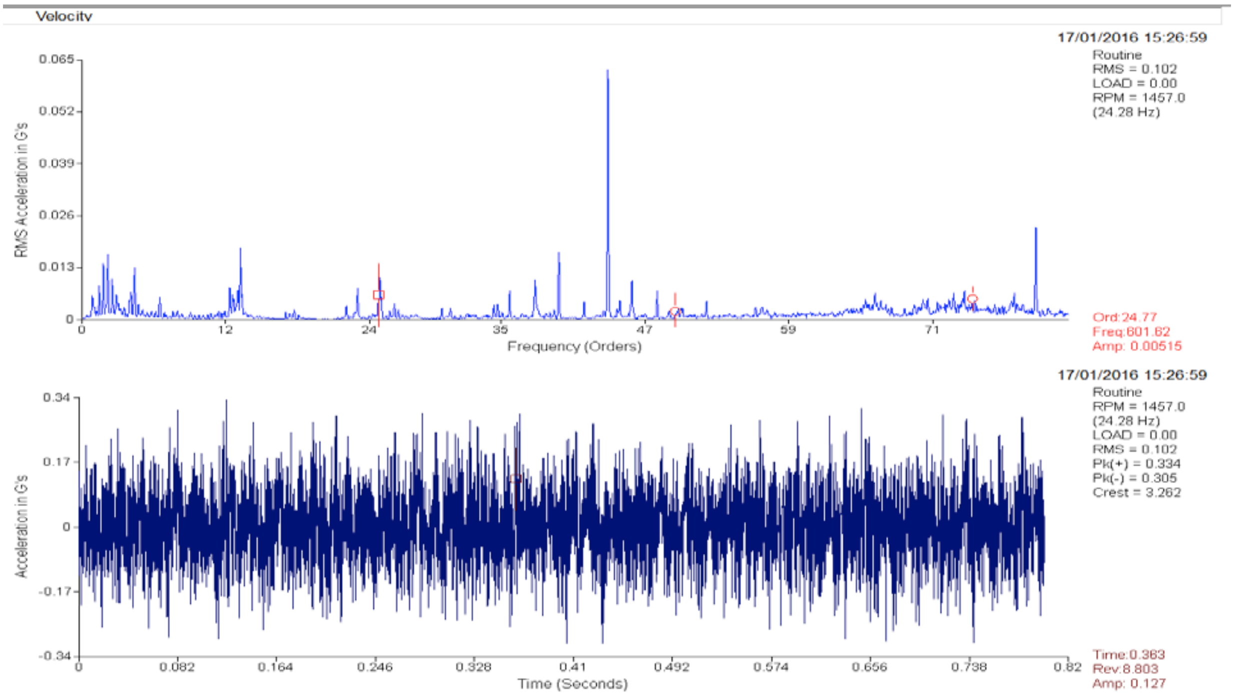


Figure 56: Motor DE spectrum and time waveform

6.3.4.2.5 Pump DE: Fault Frequencies

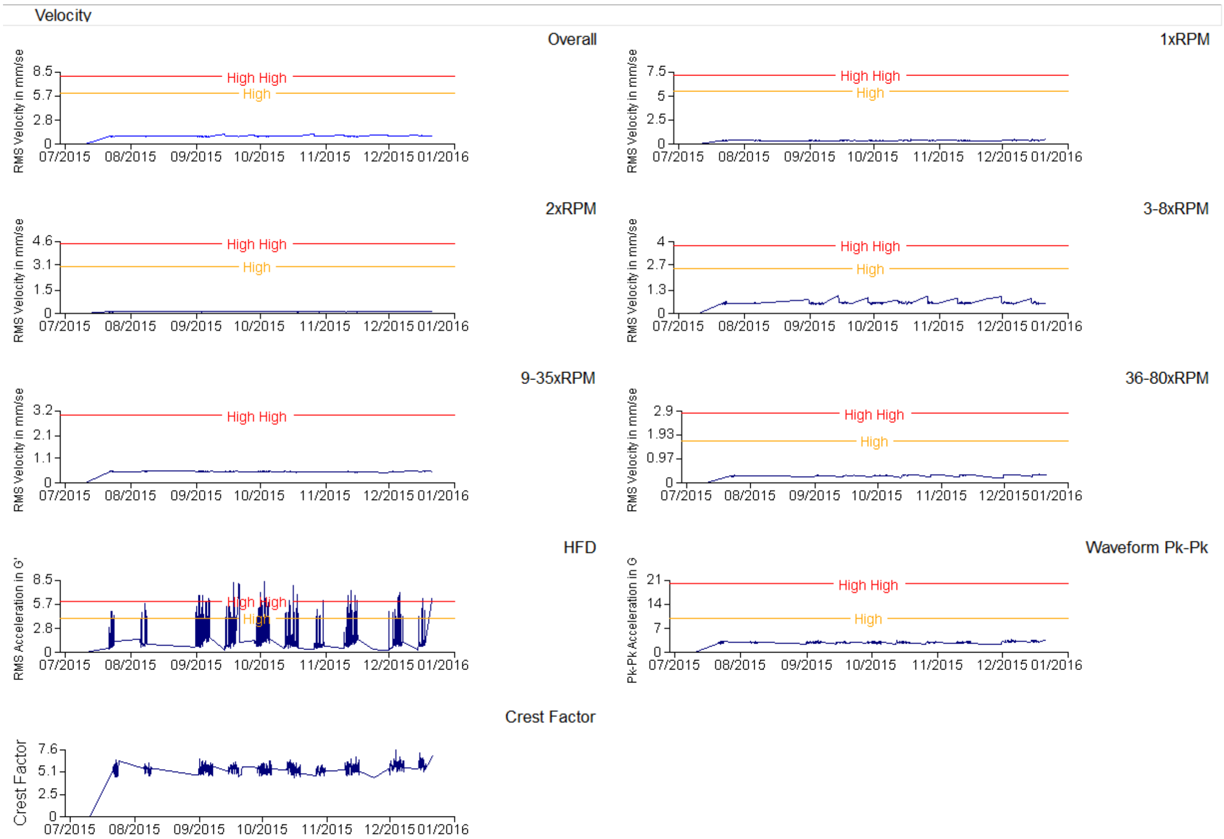


Figure 57: Pump DE velocity fault frequencies

Figure 57, illustrates that:

- The HFD trend shows periodic increase in trend values that appear to be speed related and indeed transmitted noise from the Pump NDE bearing defect identified.
- All other frequency bands are within tolerance.

6.3.4.2.6 Pump DE: PeakVue and Velocity Spectrums and Time Waveforms

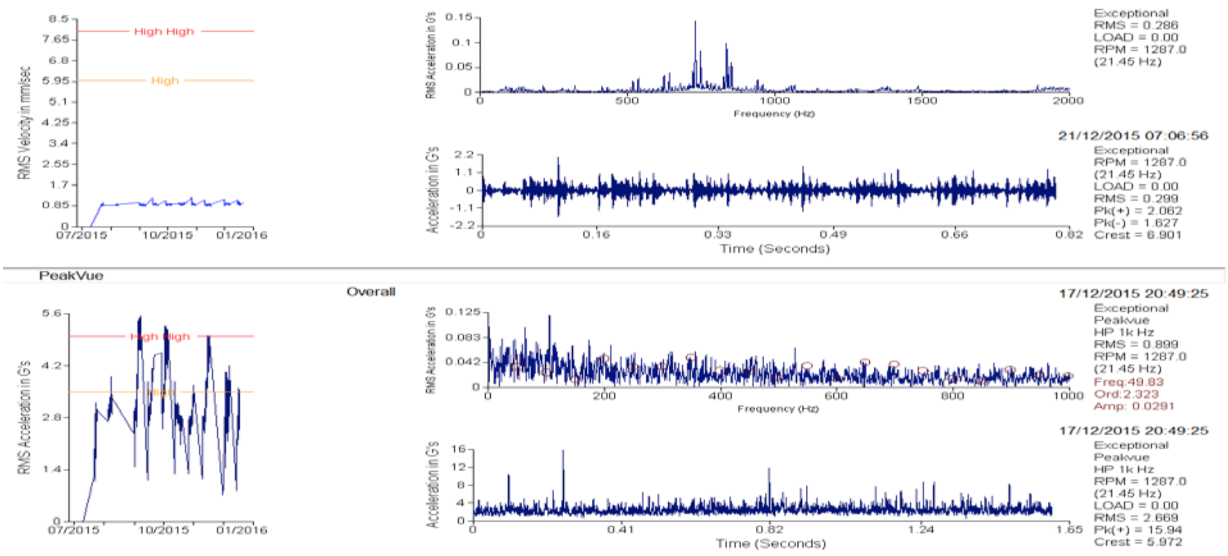


Figure 58: Pump DE overall velocity and PeakVue

Figure 58 shows healthy overall velocity and PeakVue trends. The spikes in the PeakVue trending (Figure 59 below), is speed related and noise from a defect at the Pump NDE.

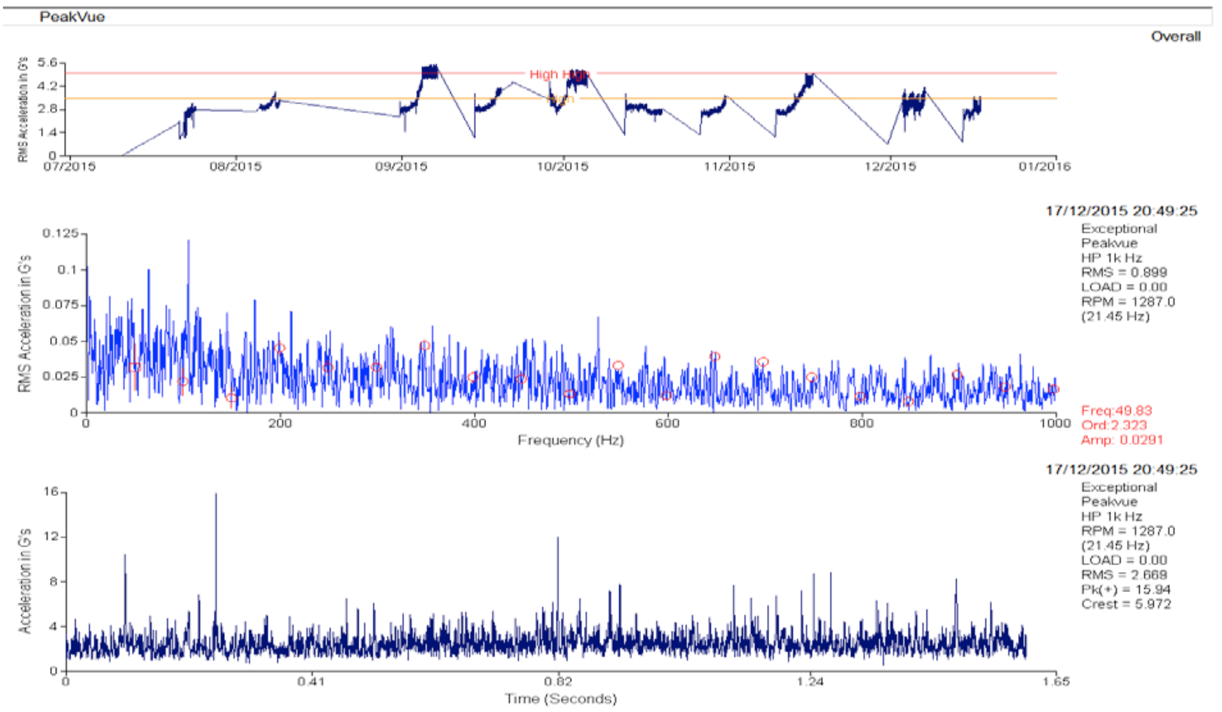


Figure 59: Pump DE PeakVue

6.3.4.2.7 Pump NDE: Fault Frequencies

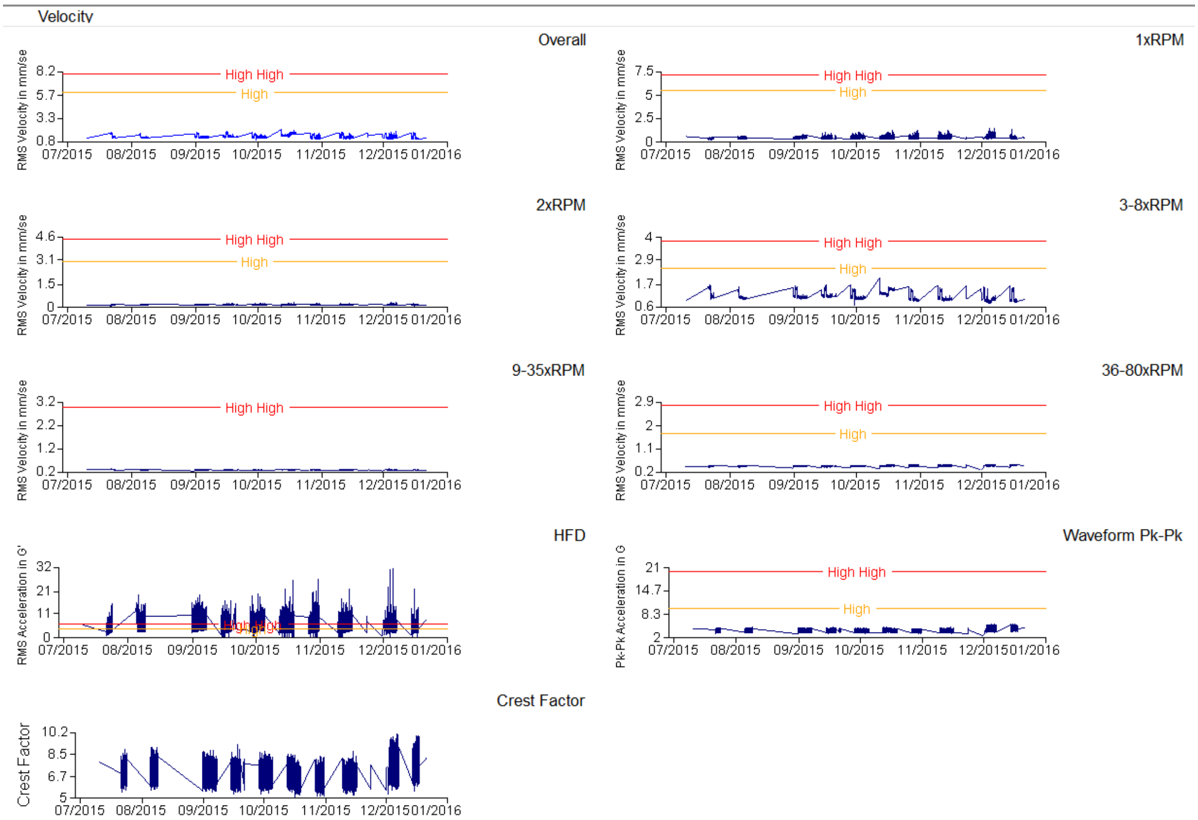


Figure 60: Pump NDE velocity fault frequencies

Figure 60, illustrates that:

- The HFD trend shows periodic increases in amplitude due to increased high frequency activity as a result of the pump bearing noise.
- The crest factor trend shows periodic increases in amplitude due a spiky / impact related signal as a result of the pump bearing noise.

6.3.4.2.8 Pump NDE: PeakVue Overall and Waveform Pk-Pk

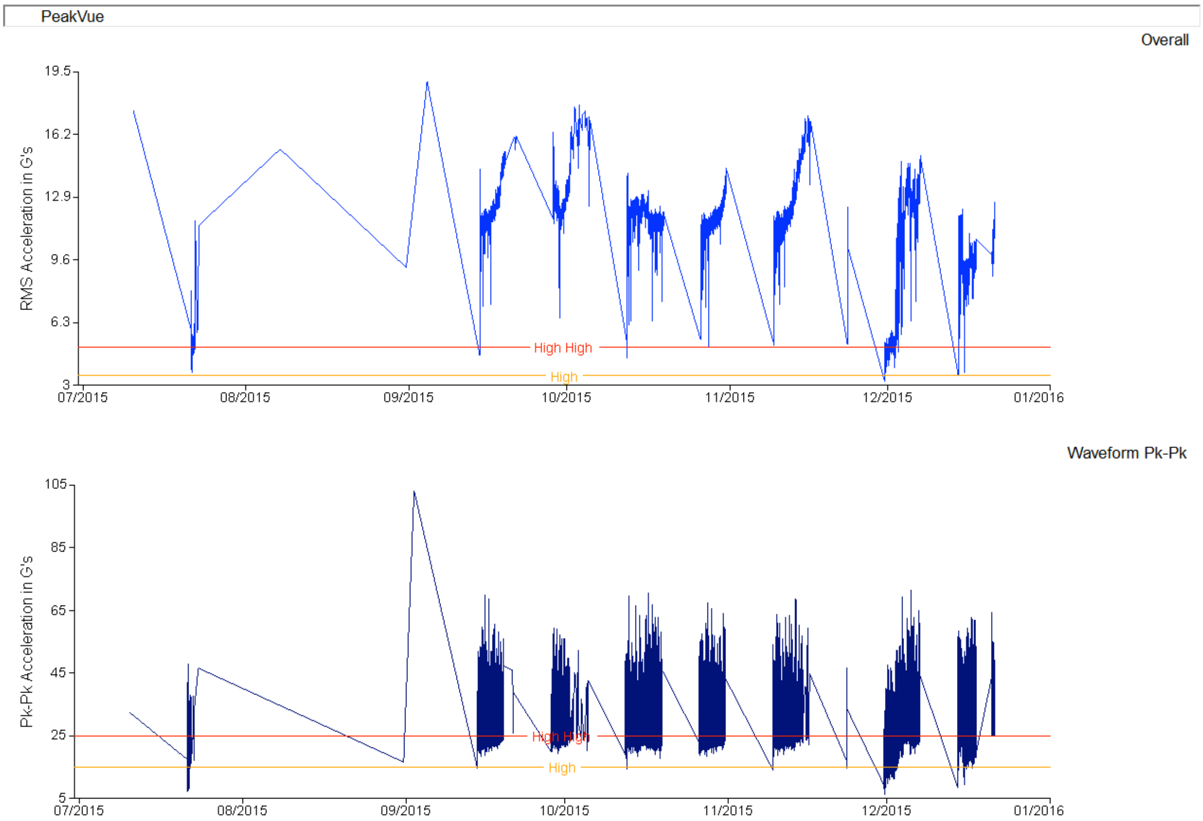


Figure 61: Pump NDE PeakVue Oveall and Waveform Pk-Pk

Figure 61 above shows high PeakVue and Waveform Pk-Pk due to significant high frequency amplitudes as a result of the pump bearing noise identified.

6.3.4.2.9 Pump NDE: Spectrums and Time Waveforms

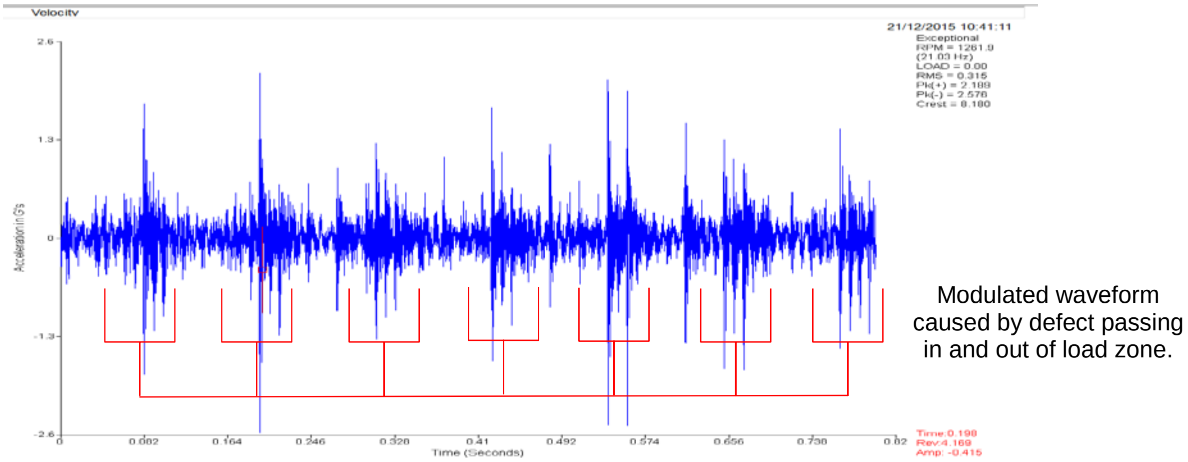


Figure 62: Pump NDE velocity time waveform

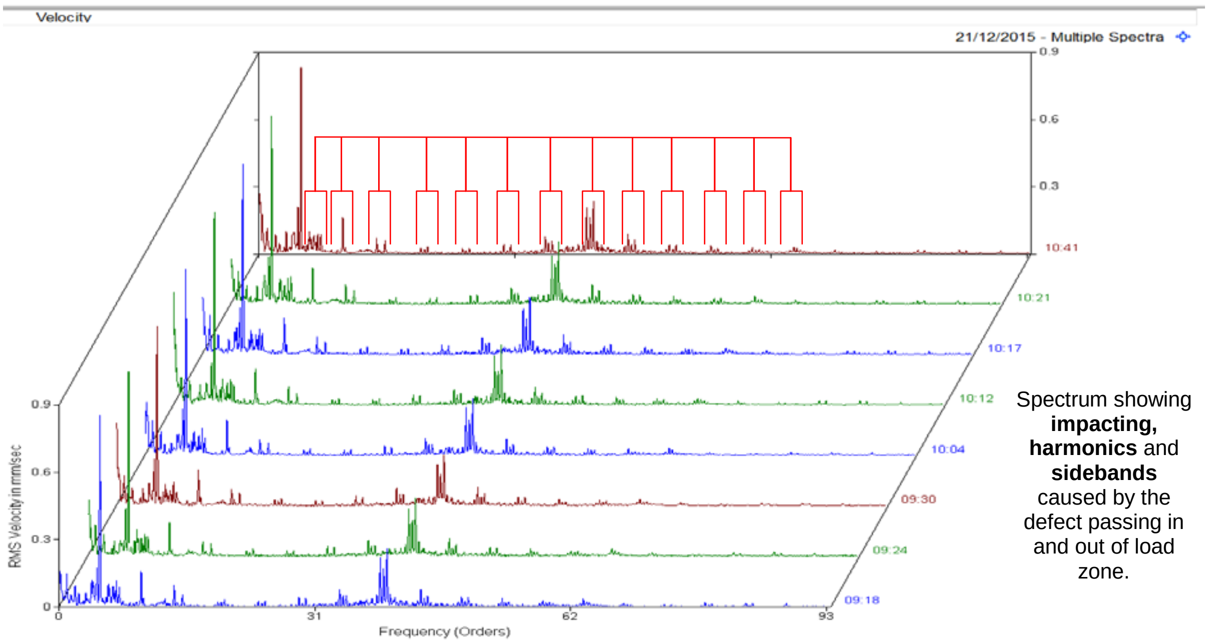


Figure 63: Pump NDE velocity spectrums

Figure 62 above shows velocity time waveform modulated by the defect passing in and out of load zone. This is further reflected in the spectrums taken over an hour time period (Figure 63).

6.3.4.2.10 Pump NDE: Comparison with Pump 23 NDE

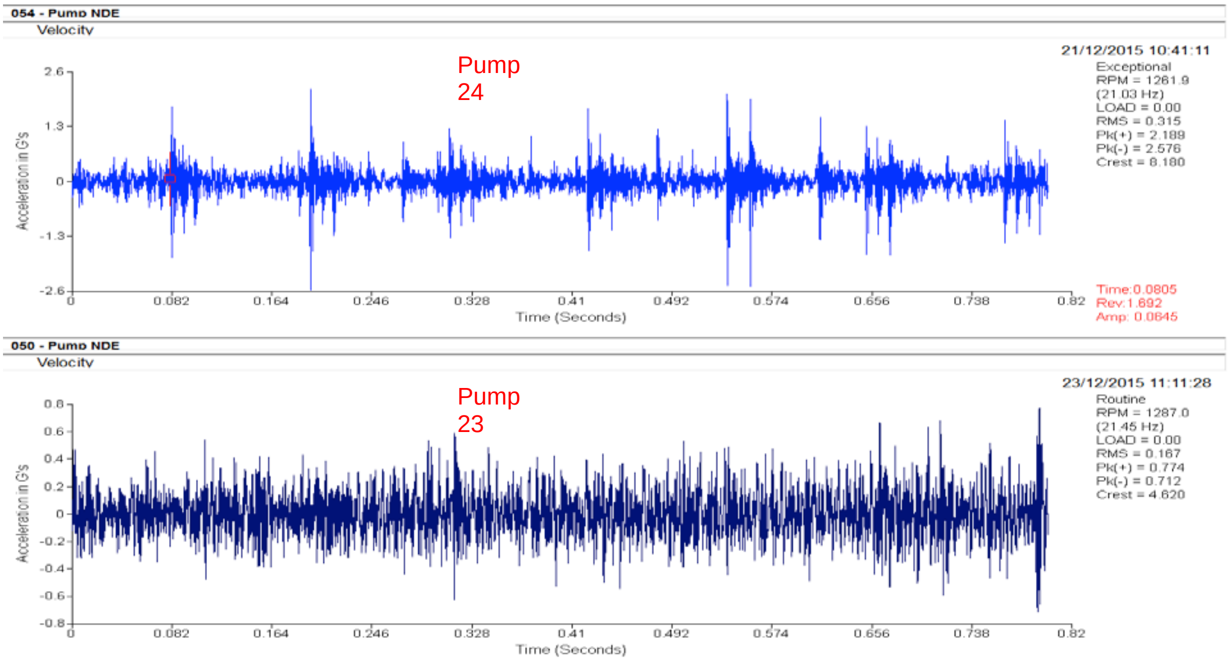


Figure 64: Pump NDE velocity time waveform comparison with Pump 23 NDE

Figures show velocity time waveforms (above) and spectrums (below) for Pump 23 NDE (healthy) and Pump 24 NDE (identified bearing defect).

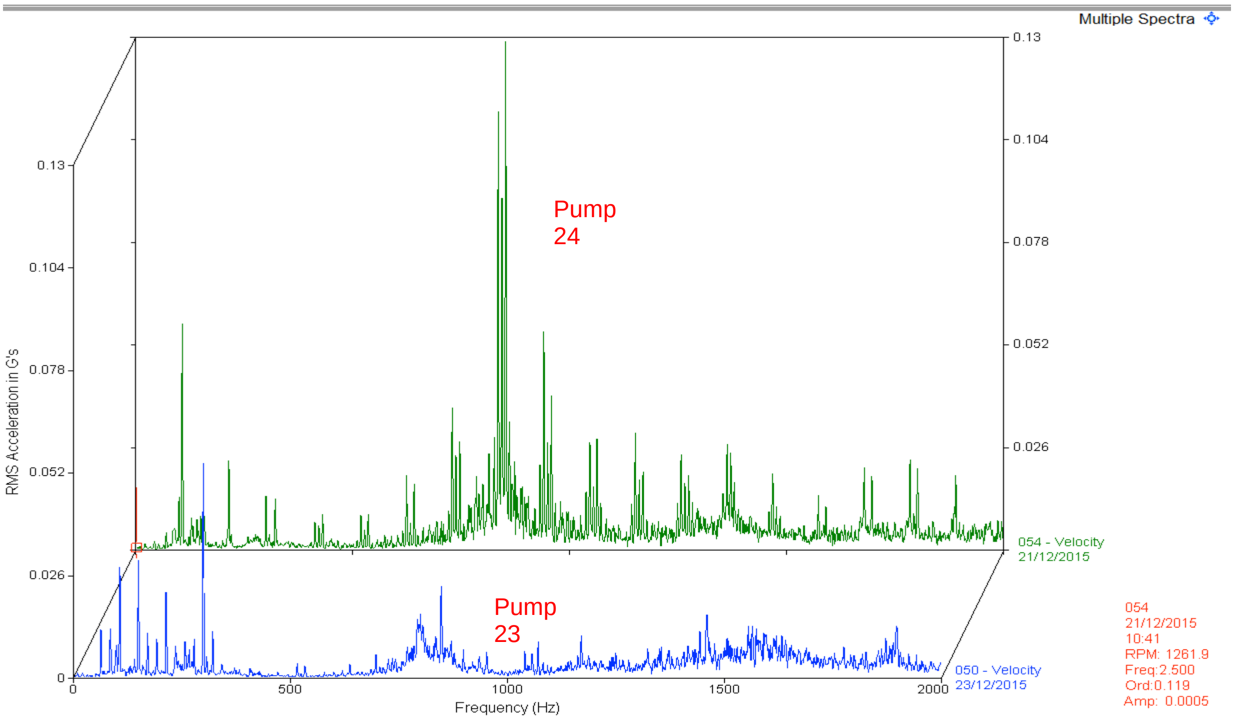


Figure 65: Pump NDE velocity spectrum comparison with Pump 23 NDE

6.3.5 KEY FINDINGS: VIBRATION ANALYSIS

The key findings from this section are:

- **Data acquisition and processing within FM:**
    - Acquiring large-scale online vibration data requires a complicated setup and installation process, which can take a long time (two month in this study).
    - A dedicated project team was necessary and numerous building pre-work protocols had to be approved before the installation could proceed.
    - Data capture from assets that are variable speed was challenging since the speed is required at the time of capturing data for vibration analysis. Additional speed converters are required.
    - The other major challenge of data acquisition was in relation to identifying when the assets are operating. This is required to prevent unnecessary data capture while the asset is stationary. A signal from the VSD is used to notify the vibration data collector when the asset is operational.
    - The data capture network can be complicated and require specialist setup.
    - Software used for data acquisition (Machinery Health Monitoring) is sufficient for fault detection and diagnosis without additional software.

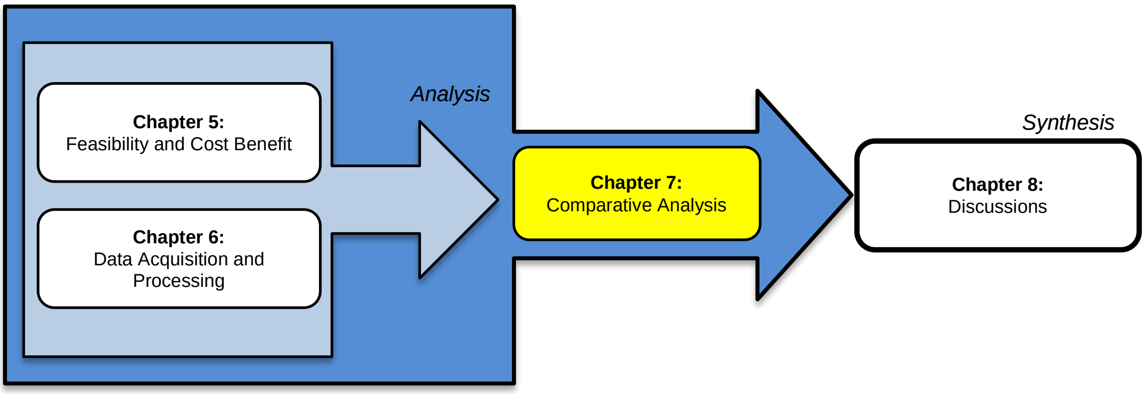
- **Analysing the processed data, indicates that:**
    - The analysis of vibration data is complex and cannot be conducted without adequate prior training and certification.
    - Vibration analysis can be used to establish the operating conditions of buildings assets.
    - Time-based PPM is not sufficient at detecting and eliminating mechanical faults, which can be achieved with vibration analysis.
    - Whilst 91% of assets in this study were analysed to be in ‘good operating condition’ in relation to ISO thresholds, 9% still had some form of a fault.
    - Vibration analysis is viable and applicable at detecting and diagnosing faults relating rotary building assets.

6.4 BOX 6: SUMMARY OF DATA ACQUISITION & PROCESSING

This chapter details the methodologies implemented to acquire and process the data for this research study, in summary:

- Plantroom temperature and relative humidity data illustrates that a significant variance of results exists within the building plantroom locations.
- Asset operation and energy consumption data demonstrated a discrepancy of operations between the assets in scope.
- A comprehensive implementation process is required for online vibration condition monitoring.
- This chapter has demonstrated a large-scale installation within a buildings context involving four networks, ten data collection wall units that incorporated with 166 accelerometers.
- Successfully demonstrated the viability of implementing of online vibration monitoring within the buildings environment by integrating the data into the BMS infrastructure.
- The vibration data collection and analysis can informed asset health conditions and identify faults that are undetectable by the traditional time-based PPM regime.

7 Comparative Analysis of Results



This is the third and final analysis of results chapter, therefore it aims to combine and cross-examine the results of the previous chapters in order to extract answers for the original research sub-questions. Moreover, in-line with the research methodology, this chapter will also describe and incorporate the qualitative ethnographic observations in to the analysis.

7.1 COMPARATIVE OVERVIEW

In the context of this study, there are three fundamental elements encompassing the overall thesis structure, which are reflected by the research objectives and sub-questions, and illustrated in Figure 66.

Firstly, in relation to research sub-question 1.1 the costs, savings and opportunities associated with the proposed transition from implementing a purely time-based policy that instigates preventive operations to a condition-based policy, which incorporates predictive actions. Chapter 5, the technical feasibility and cost benefit analysis, undertook an in-depth investigation into the key technical and commercial justification positions for implementing the proposed predictive maintenance framework.

Secondly, Chapter 6 set the foundations necessary to objectively demonstrate the practicality and viability through describing the associated data acquisition and processing requirements implemented on the case study. Lastly, this chapter combines the findings from the previous two chapters to develop answers for the overall research question and sub-questions (1.2 and 1.3).

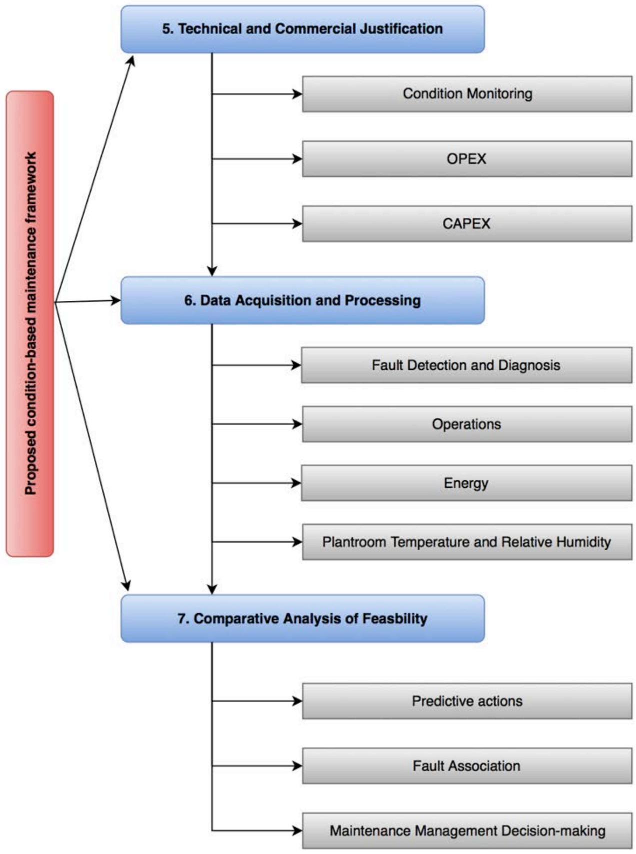


Figure 66: Key elements discussed in the core analysis chapters

7.2 ONLINE VIBRATION ANALYSIS FOR PREDICTIVE MAINTENANCE

This section aims to answer the research sub-question 1.2:

> What effect does incorporating real-time vibration analysis have on existing time-based maintenance regime?

7.2.1 IMPLEMENTATION VIABILITY

To establish the viability of CBM (as per the research design), the technical feasibility undertaken in Chapter 5 consulted external specialists to ascertain the viability of implementing an online vibration monitoring solution with the core goal of detecting and diagnosing faults to enable informed predictive maintenance actions to be executed on buildings assets. This comprehensive methodological process was also undertaken in-line with guidance from literature and international standards to ensure the practicality during the installation phases (detailed in Chapter 6). Whilst there were two significant obstacles encountered during the implementation, firstly relating to the detection of variable speed and secondly ensuring data is only collected when the asset is operational, overall the installation, data acquisition and analysis demonstrated that within the context of a building environment it is viable for online vibration to be implemented and integrated accordingly.

7.2.2 PRACTICALITY AND EFFECTS

Post installation, over the eight months of collecting and analysing asset health conditions using vibration data, the time-based PPM regime continued to be implemented on the assets. Therefore, realistically the PPM actions should have been adequate and all of the assets should have been fault free (healthy) throughout that time period. Nevertheless, as detailed in Chapter 6, using vibration analysis it was possible to detect and diagnose faults present on four assets.

Consequently, to demonstrate the effects of incorporating vibration analysis within a building maintenance context, the bearing fault results detailed in the previous chapter will be discussed further.

Firstly, the presence of the bearing fault was originally identified shortly after the completion of the installation on 22nd July. Whilst the PPM actions continued to be applied, the fault was not detected nor diagnosed via the time-based interventions.

Secondly and perhaps most significantly, as discussed in the technical feasibility and cost benefit analysis, the asset in question (IT Primary Pump P24) had new bearings installed exactly twelve months ago (see Section 5.2.4.2).

Therefore based on the capital expenditure of that assets life cycle replacement planning, the newly installed bearings should not require another change for approximately ten years, or minimum of fifty thousand hours of service life. Consequently, the observed perception of the operational maintenance personnel is naturally not to be concerned about the possibility of a fault occurring so shortly after installing new bearings.

Thirdly, as shown in Figure 67, the initial detection of the fault was achieved at the very early stages of damage (stage one of four). This would not have been possible without using vibration analysis since the damage is not yet audible to the human ear. Moreover, illustrated in Figure 67, the High Frequency Detection (HFD) analysis (first trend graph) applied 1kHz to 10kHz range filters to enable the fault to be detected and subsequently diagnosed via conducting frequency and time domain analysis (second and third graphs).

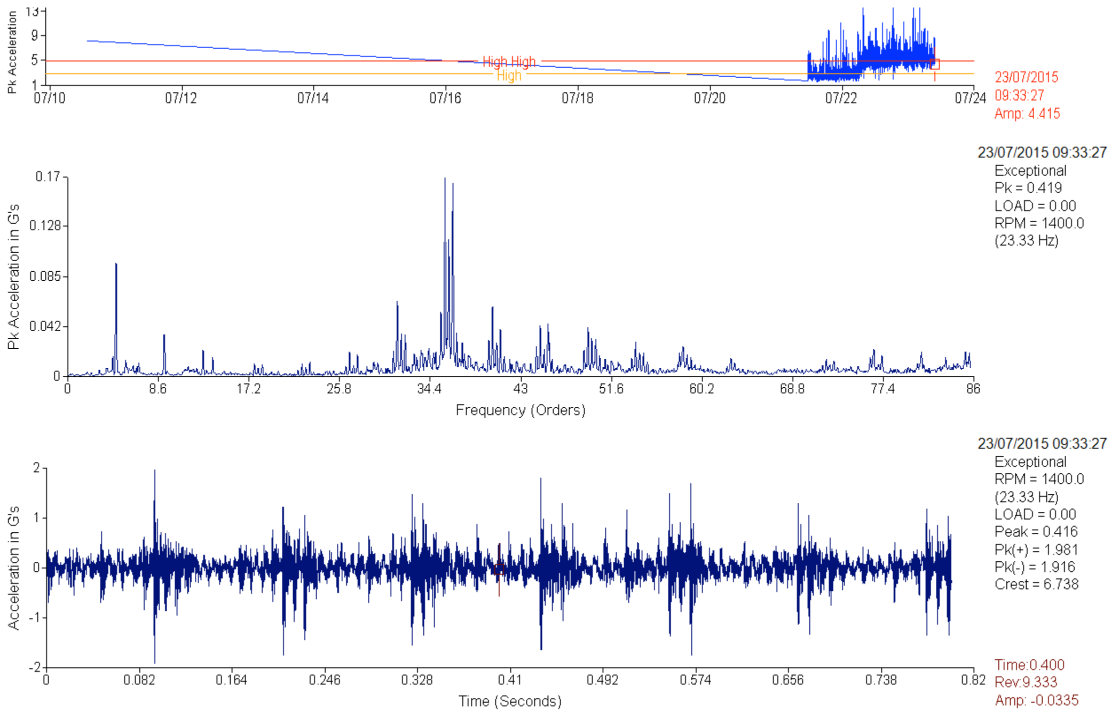


Figure 67: Initial fault detection and diagnosis data analysis in July

Fourthly, post detecting and diagnosing the bearing fault on Pump P24 the maintenance engineers investigated the asset in further detail as part of the Root Cause Analysis. The findings of this investigations established that the fault was caused by improper installation, more specifically, by inadequate fitting and tightening of a bolt. Whilst the initial damage to the bearing has been done and cannot be rectified, the detection, diagnosis and intervention to remedy the cause as a result of vibration analysis, has prevented the damage from persisting exponentially. This can be evidenced by the fact that the asset is continuing to be operational after seven months since the initial fault detection and intervention, as illustrated in Figure 68.

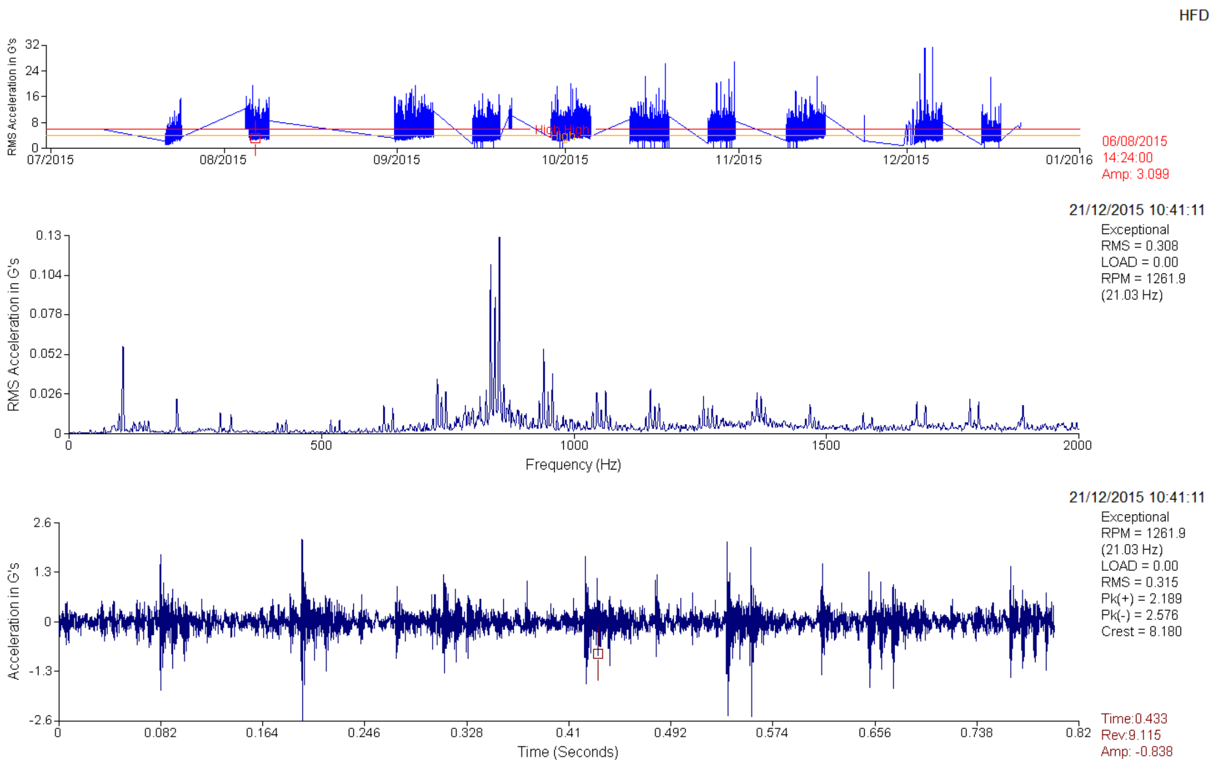


Figure 68: Data analysis showing scale of damage deterioration (July to January)

Finally, the early detection and diagnosis of this fault had several operational, tactical and strategic effects. For example, operationally, it informed that the PPM maintenance actions require checks to be carried on such loose fittings. Moreover it enabled decision-making towards a bespoke operation and monitoring plan for the faulty asset in order to reduce risk of condition deterioration caused by excess operations and/or starts and stops.

Tactically, the management control protocols that govern pre and post commissioning of bearing replacements were considered for amendment to ensure that faults due to improper installations did not occur as a result of such minor oversights. Strategically, the life cycle capital expenditure associated with that specific assets bearing replacement was adjusted with budgets allocated to enable another change sooner than originally planned.

7.2.3 RESEARCH SUB-QUESTION 1.2: KEY FINDINGS AND OBSERVATIONS

In relation to the effects and practicality of online vibration condition monitoring for maintenance management decision-making, this study has made the following observations.

The outcomes from the vibration analysis have demonstrated that the existing time-based PPM regime is not sufficient for detecting and diagnosing mechanical faults such as bearing defects. Moreover, the successful application of online vibration condition monitoring is viable within the buildings environment and can be used to inform maintenance management decision-making. Furthermore, the application of online vibration monitoring in conjunction with the existing time-based PPM regime appeared to be complimentary, especially as it enabled informed decision-making based on data analysis.

However, the complicated nature of vibration data analysis necessary to detect and diagnose faults is not a task that can be conducted by the operational personnel without adequate training and development. Nevertheless, the researcher observed substantial interest and support towards the application of CBM and vibration analysis. More specifically, at the operational level, the maintenance engineer's demonstrated a positive change of morale and attitude at the notion of applying an additional form of maintenance technique instead of the routine and somewhat considered mundane, over applied PPM actions. Furthermore, they recognised the opportunities for additional training and personal career diversification and development.

At the management and tactical levels, the added values of applying CBM decision-making were demonstrated and understood through the example of the bearing fault on IT Chilled Water Pump P24 (discussed earlier). Through the use of such analysis techniques it was possible for maintenance managers to not only mitigate daily operational risk of downtime, but also make informed coordinated logistic support decisions involving the planning, organising and delivery of spare parts (i.e. bearings), contacting specialist companies to acquire quotations and scheduling without impacting operations via downtime.

Furthermore, the managers were able to notify the strategic decision makers through evidencing the fault occurrence and detail the operational maintenance management strategy to mitigate the risks. Using such comprehensive information, the strategic asset management personnel were able to make knowledgeable decisions relating to capital life cycle expenditure and overall delivery strategy.

7.3 FAULT ASSOCIATION FINDINGS

This section aims to answer the research sub-question 1.3:

1.1. What statistical association do plantroom temperatures, relative humidity and asset energy consumption have on the occurrence of faults?

7.3.1 STATISTICAL ANALYSIS OF DATA

The online vibration analysis established the assets operating conditions and identified the assets that have fault. The results relating to the analysis of the plantroom temperature and relative humidity (Section 6.1.4) highlight the fluctuating atmospheric conditions within which the assets operate. Similarly, the energy consumption data extracted from the BMS indicates variances based on the assets conditions and hours of operations (Section 6.2.3).

Therefore, in order to test the significance and association of factors (mentioned in the research question) to causing or occurrence of fault, the collected and processed data (discussed in Chapter 6) were amalgamated into a statistical model namely, univariate and multivariate logistic regression.

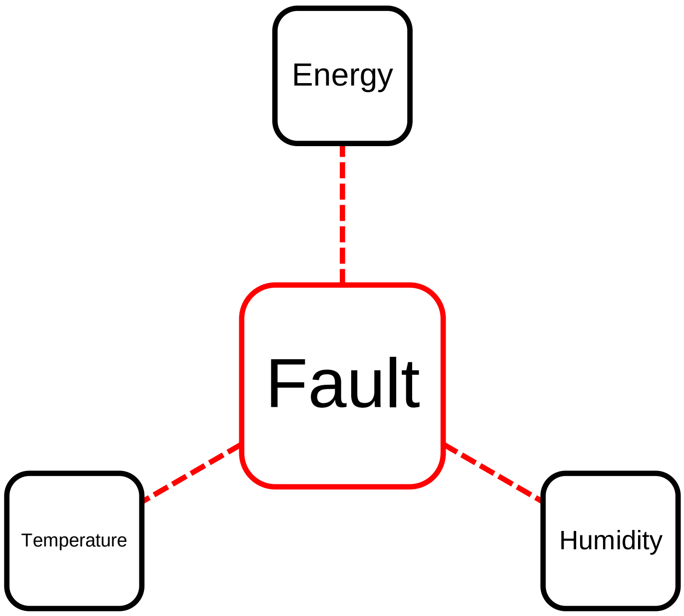


Figure 69: Univariate and Multivariate logistic regression model

7.3.1.1 Univariate and Multivariate Statistical Analysis

Univariate statistics are the foundations for majority of statistics in which a single distribution examining a single variable is analysed to enable inferences to be extracted. However, whilst this is somewhat useful, it does not allow concerns relating to association (or in other words relationships) among more than one variable to be tested (Anderson 1989).

Therefore, to conduct examinations of relationships between variables the application of bivariate statistics (two variables) is required (Anderson 1989; Hair et al. 2010). In some instances (such as this study), where there is requirement to simultaneously analyse relationships beyond the bivariate level (i.e. using two or more variables), the application of multivariate statistical analysis is necessary (Anderson 1989; Hair et al. 2010).

Some multivariate methods are an iterative extensions of univariate and bivariate such as correlation, simple regression and variance analysis, but the true goal of multivariate statistical analysis is to *'measure, explain and predict the degree of relationship among variates'* which *'cannot meaningfully be interpreted separately'* (Hair et al. 2010, p.5). This logic is valid in this study because an asset with a detected and diagnosed fault will not only be operating in the given plantroom conditions under the measured temperature and humidity, but also simultaneously consuming energy.

Furthermore, in the context of this study, as the dataset is metric and uses an interval scale (difference between two values is meaningful), the application of a multivariate regression model is most useful since it allows the size of the relationships to be estimated between the variables (Anderson 1989; Hair et al. 2010). More specifically, logistic regression is required because the single dependent variable is nonmetric and dichotomous (i.e. faulty or not faulty), and the independent variables are metric (i.e. average temperature, average relative humidity and average current) (Anderson 1989; Hair et al. 2010).

Table 42, shows how the four individually collected and processed datasets have been combined to enable the logistic regression analysis to be undertaken, i.e. the independent variables utilised the mean values and the dependent variable contained a dichotomous value.

Variables:	Fault	Temperature	Relative humidity	Current
Data / type:	Dichotomous: *Yes or No*	Metric, interval: *Mean*	Metric, interval: *Mean*	Metric, interval: *Mean*
Characteristic:	Dependent	Independent	Independent	Independent

Table 40: Variables and characteristics for logistic regression

7.3.1.2 Results: Univariate and Multivariate Logistic Regression

	Univariate level		Multivariate level	
	OR (95% CI)	**p-value**	**aOR (95% CI)**	**p-value**
Average Temperature	1.09 (1.02,1.16)	0.012	1.13 (0.97,1.31)	0.118
Average Humidity	0.95 (0.90,1.00)	0.046	1.00 (0.87,1.14)	0.983
Average Current	1.06 (1.01,1.10)	0.016	1.08 (1.02,1.15)	0.008

Table 41: Univariate and multivariate logistic regression analyses, investigating the factors associated with the occurrence of fault.

As shown in Table 43, univariate and multivariate multilevel logistic regression models provide unadjusted and adjusted odds ratios (OR and aOR) with 95% confidence intervals (CI) and p-values.

In the univariate level analysis, all three independent variables (average temperature, average humidity and average current) were significantly associated with the occurrence of fault. More specifically, increased average temperature was associated with increased risk of fault. As shown in Table 43, the results from the analysis suggest that per one degree Celsius increase of the average temperature there was a 9% increase in the fault, odd ratio 1.09 (95% CI 1.02-1.16), p=0.012. In contrast (although logically valid), per unit increase of the average humidity there was a 5% decreased fault OR 0.95 (95% CI 0.90-1.00), whereas increased average current was associated with 6% increased fault.

In the multivariate analysis, after adjusting for all factors simultaneously, only increased average current was associated with increased fault. For every one Ampere increase of the average current, there was an 8% increase in the fault aOR 1.08 (95% CI 1.02-1.15), p=0.008.

7.3.2 RESEARCH SUB-QUESTION 1.3: FINDINGS AND INTERPRETATIONS

The results of the statistical analysis enable the following three inferences to be stated.

Firstly, the univariate finding relating to increased temperature being associated with increased probability of fault occurrence supports the findings concerning the association of increased humidity reducing the risk of fault, because as the humidity increases there is more moisture present thus temperature is expected to be reduced.

Secondly, Plantrooms that have higher atmospheric temperatures (thus reduced humidity) have a high probability of faults occurring since the findings from both univariate temperature and humidity are applicable, this finding is relevant to Plantroom A and suggests that the conditions could be contributing towards a greater risk of fault occurrence (although only one asset has been identified at this location to be faulty).

Lastly, the findings relating to energy consumption (average Current) indicate the presence of an association not only at the univariate level, but also at the multivariate level. Therefore, beyond the realms of individually testing the independent variables, it can be deduced that the simultaneous testing of the three independent variables advocates that higher consumption of Current by assets is a symptom of faults being present as the risk is statistically significant and increased.

For example, in relation to the asset with the identified bearing fault (Pump P24), the descriptive results of mean Current associated with this asset appears to be noticeable higher than the other assets (see Section 6.2.3, Table 37, Asset CHW_P24).

Therefore, based on these findings it should be possible to model a baseline consumption of current for all assets and in the event the consumption increases outside the set threshold initiate some form of maintenance action. This could provide an inexpensive maintenance decision-making tool that can be easily applied to all assets and monitored through the existing BMS.

7.4 SUMMARY OF COMPARATIVE FINDINGS

This section combines all relevant findings and also highlights any incidental analysis and outcomes, such as the asset operations results.

7.4.1 ASSET OPERATIONS

Although research sub-question 1.1 has been analysed in Chapter 5, the data capture and analysis of asset operations and energy consumption (Chapter 6) has provided an opportunity to reflect and relate findings back to the original feasibility analysis. For example, the analysis identified two noteworthy operational characteristic relating to the case and assets in scope.

Firstly, with the exception of the AHUs, all assets are under a duty/standby configuration with the core goal of reducing risk of fault, failure and disruption to service provisions through ensuring that in the event a duty asset fails or becomes faulty, the replica fault free standby asset can be immediately deployed. The changeover from duty to standby is automated via the BMS. The feasibility investigation identified that the BMS has been configured to ensure a ratio of 50:50 usage is scheduled.

However, the actual operations results analysed in section 6.2.3 emphasise a discrepancy of between 10 per cent and 16 per cent. Therefore, further analysis of the duty/standby arrangement is necessary to understand potential reasoning behind this discrepancy.

Secondly, the operations strategy is directly linked to OPEX. The time-based preventive maintenance strategy applied on the assets have the same frequency namely, Monthly, Three Monthly and Annually. Therefore, the strategy employed for these PPM actions are implemented on the belief that the scheduled operations are the same as actual, i.e. the assets operate the same number of hours thus require the same frequency of maintenance actions. In addition, the scheduled hours of operations has also been identified as a significant consideration towards the CAPEX life cycle replacements, which in the context of rotary assets relate to the replacement of bearings. The analysis of bearing life highlighted a significant shortfall of life being achieved (in comparison to industry and literature guidelines).

Yet, according to the actual operations results (section 6.2.3), the operations vary significantly. For example, in the basement locations the difference is as much as 81 per cent, while in the Roof location it’s even greater at 91 per cent.

Therefore, scheduled and actual hours of operations are further analysed in the following section, and observations are provided in relation to the duty/standby changeover configurations.

7.4.1.1 Scheduled vs. Actual Operations

The operations results detailed in section 6.2.3 highlight a discrepancy between the feasibility analysis ‘scheduled’ hours of operations and the ‘actual’ hours of operations extracted from the VSD datasets, this is summarised in Table 43.

	Hours	**Energy (kWh)**	**Energy Cost**
Actual:	82,924	2,296,377	£183,710.13
Scheduled:	119,130	3,547,440	£283,795.20
Difference:	*-36,206*	*-1,251,063*	*-£100,085.07*
% Difference:	*-30%*	*-35%*	*-35%*

Table 42: Summary of actual vs. scheduled operations, energy consumption and cost

The comparison of actual operations against scheduled indicates that actual operations is 30% less (36,206 hours). Moreover, energy consumption is 35% less, which consequently is reflected on the cost.

However, as highlighted in (6.2.4), the data collected from the VSD encountered several obstacles. For example, due to limitations with the buildings IT network, there were several weeks of data missing which cannot be accounted for in this comparison. Moreover, since it was not possible to obtain actual operations and energy data for five assets in the Chiller Plantroom, these assets had to excluded from the comparison. Therefore although this analysis reveals that assets are operating less than scheduled, the total degree of difference in reality may be much lower.

7.4.1.1.1 AHU Fans

The AHU fans were identified to be the most operated assets on the Roof locations. Analysing the results in comparison to the feasibility analysis emphasis two key findings.

Firstly, although the feasibility analysis with the BMS ‘scheduled’ dataset merged the supply and extract fans together, the VSD dataset (the actual operating hours) provided detailed data relating to each fan. Therefore, it was possible to analyse the fans individually based on the captured and processed dataset.

Secondly, the fans are scheduled to operate approximately 3,120 hours annually (based on a 13 hour per day cycle). However, as shown in Figure 70, the actual operating hours for the AHU fans were significantly greater than the scheduled, more specifically the differences appeared to be 26 to 35 per cent greater.

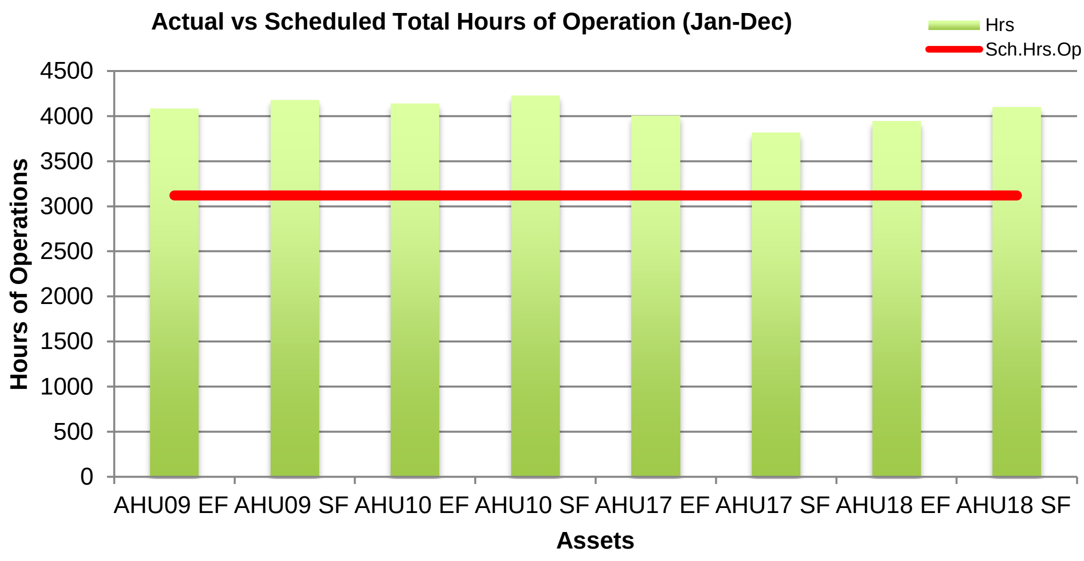


Figure 70: AHU Fans total actual hours of operations against the scheduled

7.4.1.2 Key Observations: Duty/Standby Change

Whilst the BMS is automated to operate assets based on a prescribed scheduled routine, the buildings operational personnel have the capability to override the configuration, thus amending the duty and standby setup. The main reason provided for enabling such functionality is that an asset needs to be switched off (i.e. turned from duty to standby) in order to undertake maintenance or in the event of a fault and/or failure. Although the logic is valid, the researcher observed no set guidelines, procedures or management approval requirements being implemented to provide control of these changes.

Consequently, in practice there appeared to be numerous unexplainable changeovers from duty to standby, and vice versa. Furthermore, when a changeover does take place to commence maintenance, post maintenance the original configurations do not get restored.

This observation can be evidenced using the collected operations data from the VSD, demonstrated in Figure 71. The Current consumption of two pumps (CHW P23 and CHW P24) is visualised in detail over time, day and month for consecutive months to emphasis the operational patterns. The changeover for these pumps is automated on weekly basis (Mondays at 10:15), however as illustrated there are numerous interventions. In December, the first week changeover from P23 (blue) to P24 (red) takes place as scheduled, but the change is manually reversed one day after (Tuesday 09:30). This is also the case the following week, where two days after the automatic changeover the operations are manually reverted. Yet, no manual change is implemented during the final weeks of the month. Moreover, there is a similar manual changeover pattern in January. Hence, over the two months illustrated in Figure 71, pump 24 (red) has not only operated more hours than scheduled in comparison to its replica, but also turning on and off more often.

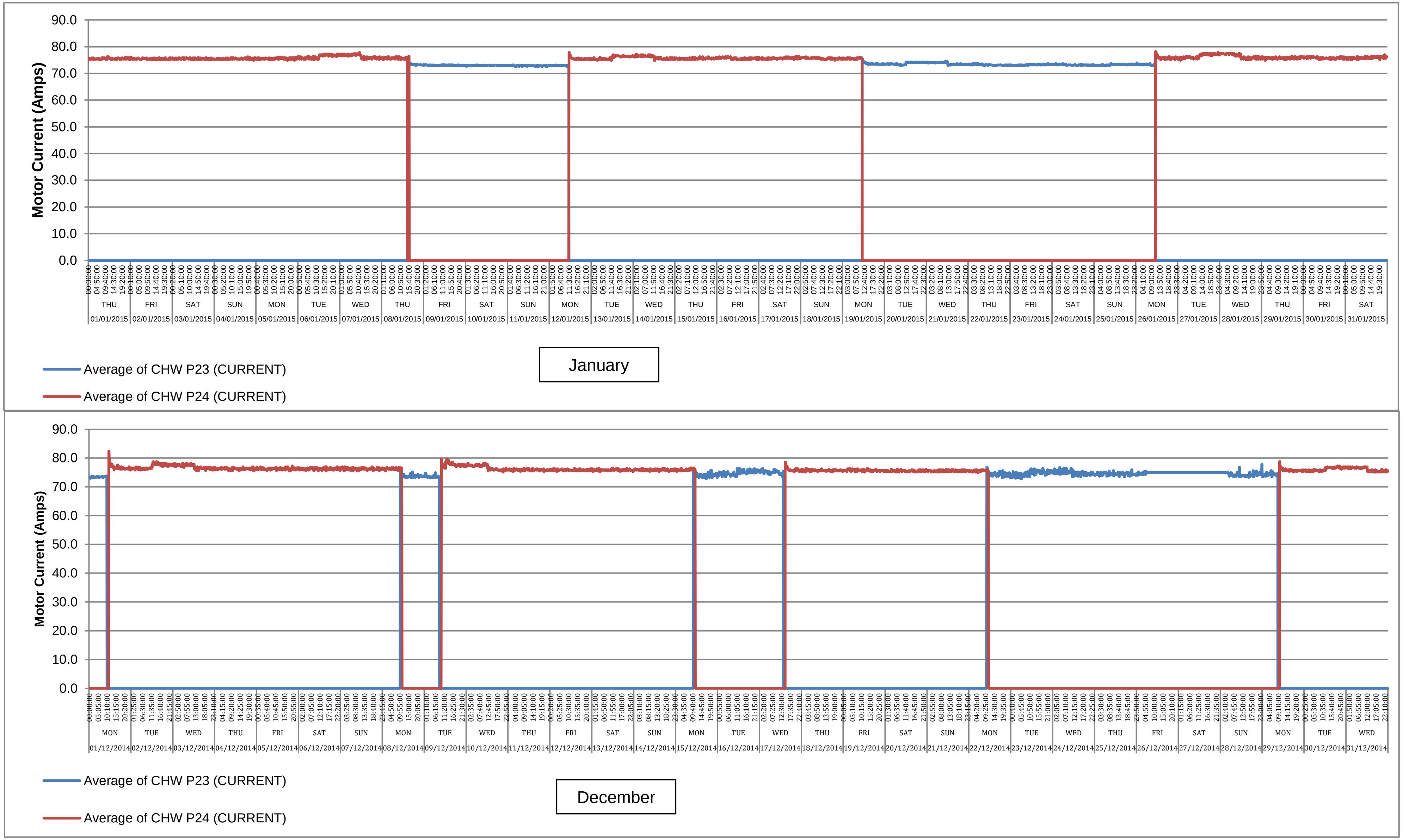


Figure 71: Pumps P23 and P24 operations per day for December and January

7.4.2 IMPACTS OF IMPLEMENTING CBM POLICIES

The main research question in this thesis set out to explore the impacts of implementing CBM policies in a building maintenance context, therefore based on the empirical findings highlighted in Chapter 5, Chapter 6 and in this chapter, the following observations can be made:

Firstly, the technical and economical feasibility analysis highlighted the relevant costs and potential savings and opportunities associated with implementing an online CBM that utilises online vibration condition monitoring. The findings from this in-depth comparative analysis identified numerous opportunities for adopting the proposed third-generation maintenance concept, including significant OPEX saving opportunity (£541,464.14) and CAPEX savings (£250,000). In addition to the financial saving opportunities, the analysis also indicated a variety of unquantifiable impacts that would have a beneficial impact to overall maintenance management and operations, for example the ability to make better informed life cycle decisions, improve quality of service through reduction of unplanned downtime and reduce risk through evidencing condition of assets.

Secondly, the technical feasibility was established through specialist consultants during the analysis stage and demonstrated in practice through the implementation of sensor data acquisition and processing. This indicated the practicality and viability impacts of implementing the proposed CBM solution. Furthermore, the analysis of the quantitative datasets highlighted several discrepancies relating to asset operations and a concerning variance of results relating to the plantroom temperatures and relative humidity, which combine to provide a greater awareness of specific asset maintenance management requirements.

For example, the findings from asset operations analysis not only raises question on the scheduled hours used by senior management to conduct life cycle planning and replacements, but also the strategy of implementing a 50:50 ratio of operations and the assets requirements for maintenance. Evidently, it would appear that one asset is operating more hours, whilst the other is being turned on and off more often, such operational characteristics naturally contribute towards bespoke maintenance requirements and increased possibility for the inception of faults.

Thirdly, in relation to the practical installation of online vibration monitoring hardware, the findings from Chapter 6 indicate that several obstacles can impact the process, such the dynamic buildings assets that operate on variable speeds (rather than fixed speed) and the ability to only collect data when the asset is operational to prevent unnecessary data collection. However, this study demonstrated that it is possible to develop solutions to resolve these obstacles and ensure a successful technical implementation. Moreover, the BMS infrastructure within the building appeared to aid the resolution of such obstacles and enable the overall data acquisition and data management.

Fourthly, the overall data analysis demonstrated the health condition of the assets and highlighted insufficiencies associated with the time-based PPM actions and existing post-installation protocols relating to bearing replacement. Moreover, having such in-depth information regarding early fault detection and diagnosis indicated positive planning, logistical support and operational awareness impacts across all management levels.

Lastly, the online vibration monitoring generated large-scale complex datasets that required detailed analysis using expert knowledge. This naturally demonstrated challenges relating to unskilled management personnel conducting data interpretations to inform maintenance management decision-making. However, the significant value of real-time asset health and usage monitoring in conjunction with adequate vibration data analysis exhibited in this study further emphasised the necessity to incorporate such techniques within the overall maintenance strategy. Moreover, the use of such technology and data driven methods positively impacted the morale of all the maintenance personnel, whom demonstrated keenness towards contemporary alternatives of conducting and managing maintenance.

Nevertheless, whilst there are several positive impacts of implementing CBM policies, a fundamental negative is that the numerous datasets that have been collected and analysed in this study relating to asset condition, operations, energy consumption and environmental condition remain incoherent, isolated and difficult to interpret within the existing building maintenance management processes. Therefore, a cohesive management decision support tool is required to inform and enable easier data interpretations and decision-making at all levels (strategic, tactical and operational). This is particularly necessary since majority of the building management personnel do not have the time, nor the comprehensive technical knowledge and expertise of complex data manipulation and analysis. This is further explored in the next section of this chapter.

7.5 MAINTENANCE DECISION SUPPORT VISUALISATION

The core goal of this project is to enable building maintenance management decision-making through condition monitoring and data analysis. Yet one of the key findings identified from the implementation of online vibration analysis (6.3.5) relates to the complexity of vibration data and the challenges of making valid interpretations without adequate prior training, which may hinder the uptake of the proposed predictive maintenance framework and contribute towards yet another isolated CBM installation that is unable to demonstrate successful business process integration (as discussed in the literature).

Therefore, to combat this concern, as shown in Figure 72, it was necessary to develop a tool that not only amalgamates and embraces the findings discussed in this chapter, but also enables the complex datasets to be easily interpreted thus adequately supporting management decisions. Consequently, in order to achieve this aim the numerous datasets from this study were integrated with the central system that is known to all stakeholders (i.e. the BMS) and four bespoke visual maintenance support dashboards were created. Furthermore, to ensure suitability, the dashboards were developed via iterative consultations with users and the EngD board members.

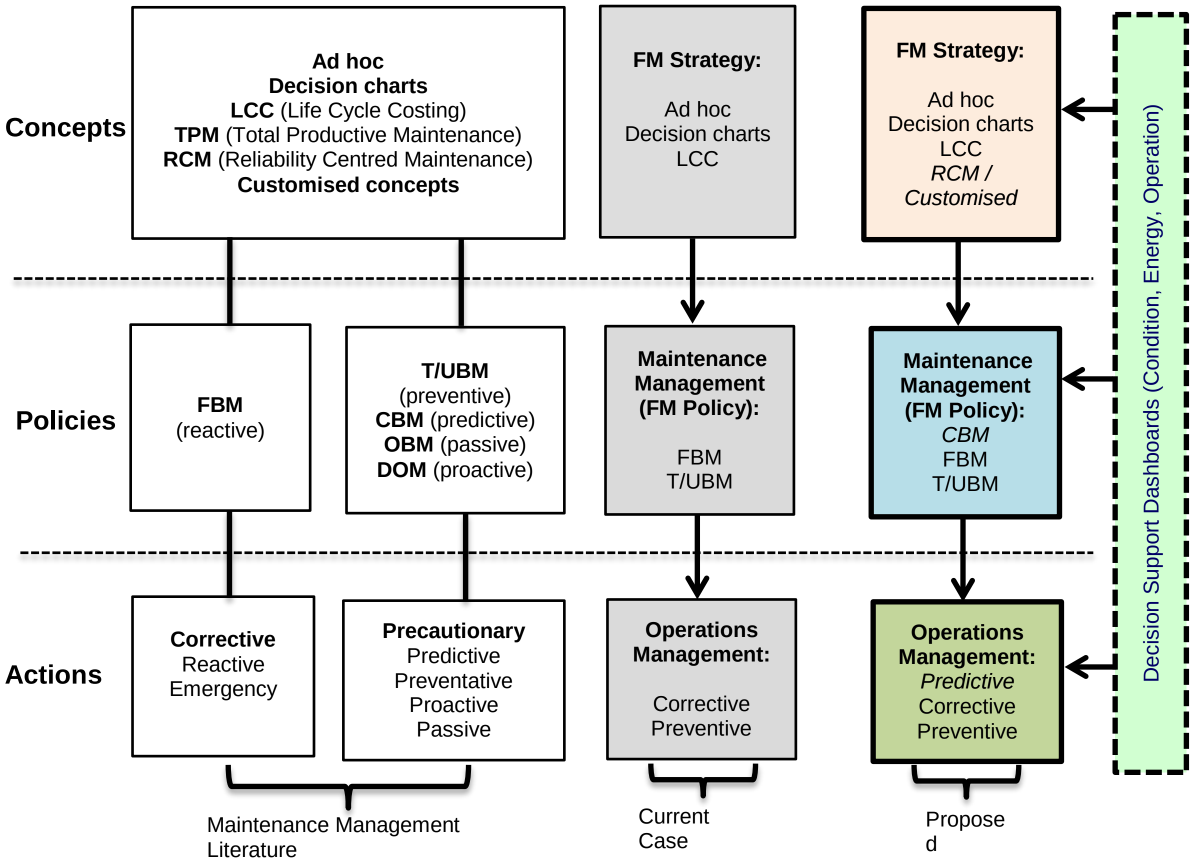


Figure 72: Decision support dashboard input into proposed maintenance framework

1. Plantroom condition (Figure 73): This screen provides an overview of the assets, and more specifically the temperatures and relative humidity associated with the plantroom location. Moreover, the Carbon emission factor can be specified here. This screen not only informs the maintenance personnel of the conditions at any given time, but also enables decision to be made relating to working in certain locations that may have temperatures exceeding health and safety working practices.

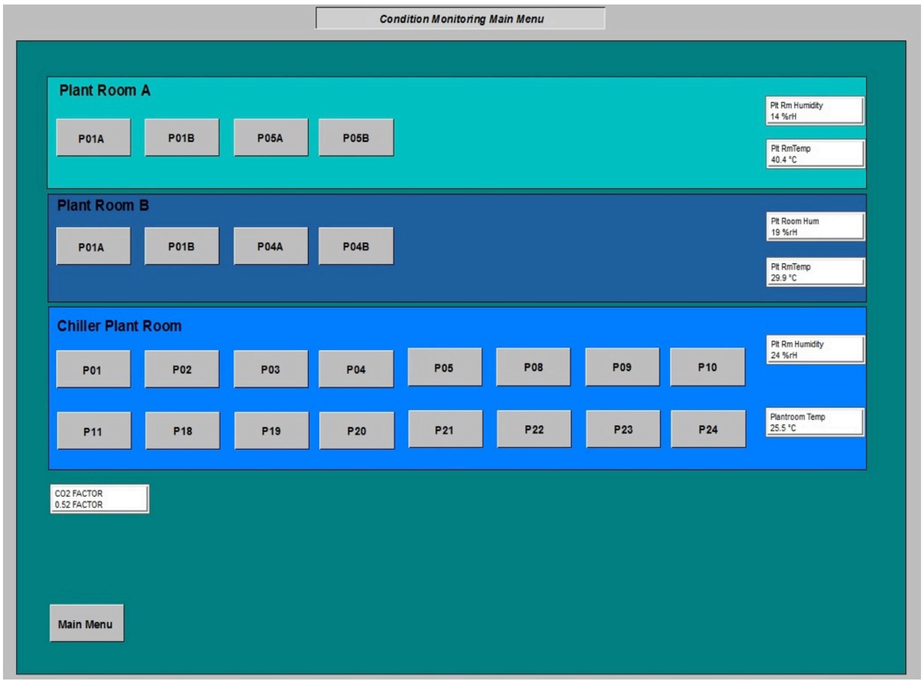


Figure 73: Dashboard: Overview location conditions

2. Overall health condition (Figure 74): This screen provides an indication of the assets overall health using a red, amber, green (RAG) status. The status is based on the real-time vibration data that has been integrated in the BMS from the online vibration monitoring system. This will enable maintenance manager, engineers and non-technical personnel to easily and quickly establish the condition of an asset.

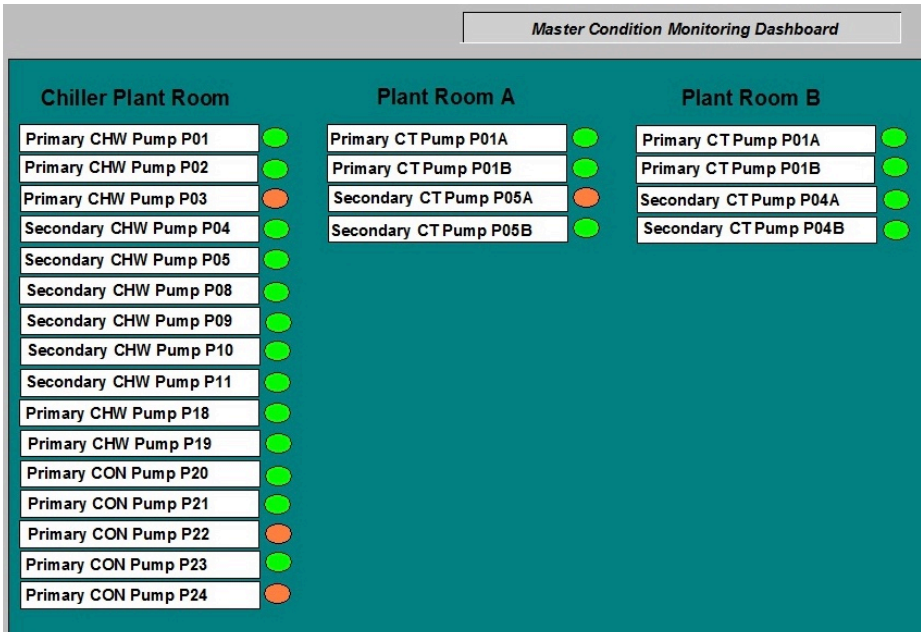
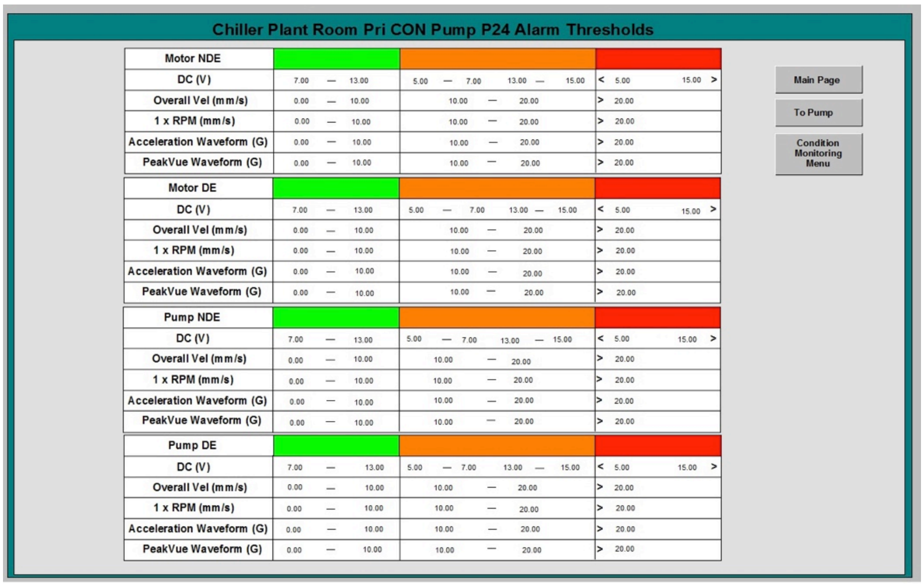


Figure 74: Dashboard: Overall asset health condition

3. Threshold for RAG alarm status (Figure 75): The vibration tolerances for each asset is specified in this screen to either reflect the ISO Standard (as default), or based on the operational requirements. The tolerance thresholds are programmable for all 166 accelerometers. Moreover, the reliability of the accelerometer itself is also validated through integrating thresholds for the DC voltage.



Motor NDE			
DC (V)	7.00 — 13.00	5.00 — 7.00 13.00 — 15.00	< 5.00 15.00 >
Overall Vel (mm/s)	0.00 — 10.00	10.00 — 20.00	> 20.00
1 x RPM (mm/s)	0.00 — 10.00	10.00 — 20.00	> 20.00
Acceleration Waveform (G)	0.00 — 10.00	10.00 — 20.00	> 20.00
PeakVue Waveform (G)	0.00 — 10.00	10.00 — 20.00	> 20.00
Motor DE			
DC (V)	7.00 — 13.00	5.00 — 7.00 13.00 — 15.00	< 5.00 15.00 >
Overall Vel (mm/s)	0.00 — 10.00	10.00 — 20.00	> 20.00
1 x RPM (mm/s)	0.00 — 10.00	10.00 — 20.00	> 20.00
Acceleration Waveform (G)	0.00 — 10.00	10.00 — 20.00	> 20.00
PeakVue Waveform (G)	0.00 — 10.00	10.00 — 20.00	> 20.00
Pump NDE			
DC (V)	7.00 — 13.00	5.00 — 7.00 13.00 — 15.00	< 5.00 15.00 >
Overall Vel (mm/s)	0.00 — 10.00	10.00 — 20.00	> 20.00
1 x RPM (mm/s)	0.00 — 10.00	10.00 — 20.00	> 20.00
Acceleration Waveform (G)	0.00 — 10.00	10.00 — 20.00	> 20.00
PeakVue Waveform (G)	0.00 — 10.00	10.00 — 20.00	> 20.00
Pump DE			
DC (V)	7.00 — 13.00	5.00 — 7.00 13.00 — 15.00	< 5.00 15.00 >
Overall Vel (mm/s)	0.00 — 10.00	10.00 — 20.00	> 20.00
1 x RPM (mm/s)	0.00 — 10.00	10.00 — 20.00	> 20.00
Acceleration Waveform (G)	0.00 — 10.00	10.00 — 20.00	> 20.00
PeakVue Waveform (G)	0.00 — 10.00	10.00 — 20.00	> 20.00

Figure 75: Dashboard: Thresholds alarm status for each accelerometer

4. Detailed asset condition monitoring (Figure 76): This is the detailed data visualisation page. It amalgamates the key findings discussed in this chapter and numerous datasets investigated in this study to enable informed maintenance management decision-making.

Firstly, the asset's online vibration data analysis is visualised in the centre of the screen. The four accelerometers connected to the asset are given a primary alarm status (RAG) based on the five secondary condition thresholds set in the threshold page (Figure 75). This is real-time data extracted from the third-party online vibration analysis solution (MHM software).

Secondly, the weekly scheduled and actual operating hours are visualised on the bottom left-hand corner, any discrepancies will be easily detected and rectified accordingly.

Thirdly, the weekly energy consumption and associated Carbon emissions are visualised on the right-hand side of the screen.

Finally, real-time circular dials indicate various operational characteristics such as Current, CO_2, kW, speed and torque associated with the asset at any given time of operation.

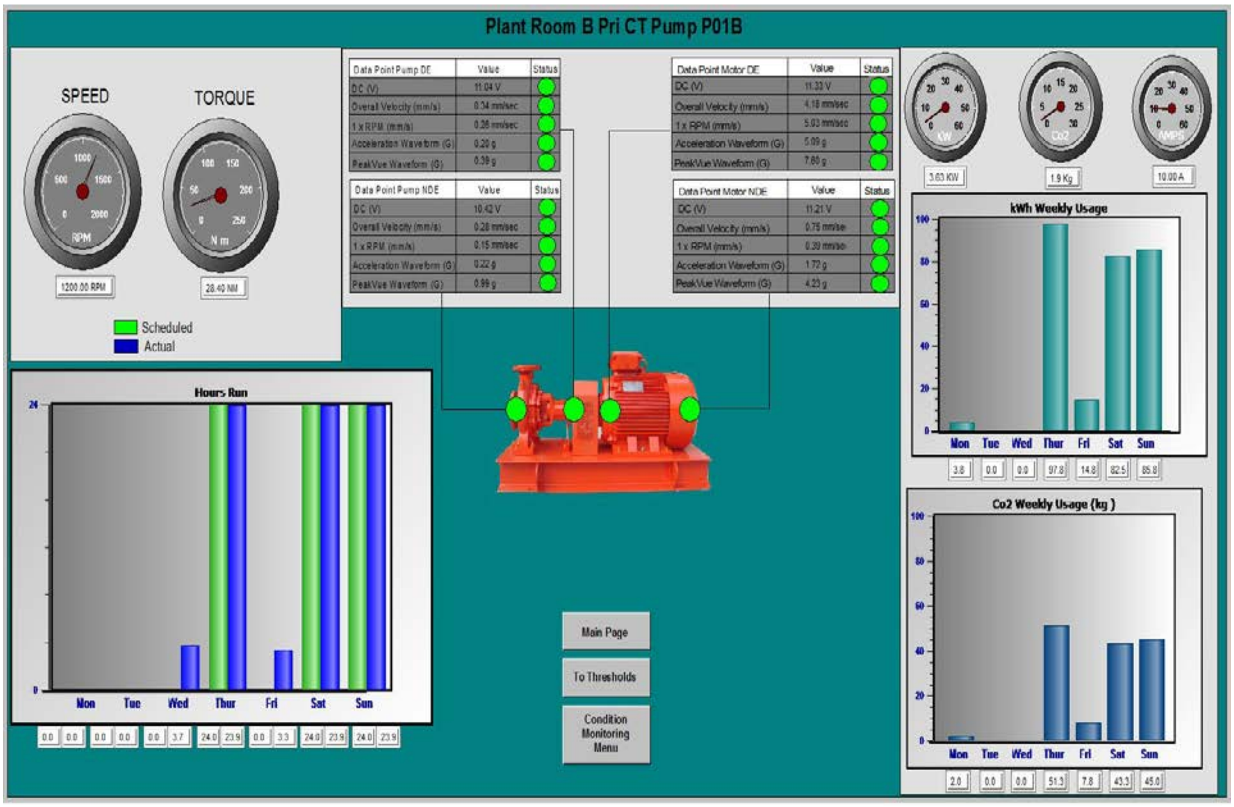


Figure 76: Dashboard: Detailed asset condition monitoring

Finally, to further enhance the business process integration, the dashboards are presented on dedicated displays that are wall mounted within the relevant maintenance management offices and workshops (as shown in Figure 77). Moreover, to aid the vibration analysis process and promote further awareness and support, detailed fault characteristic wall charts have also been displayed in the relevant areas (an example is shown in Figure 78).

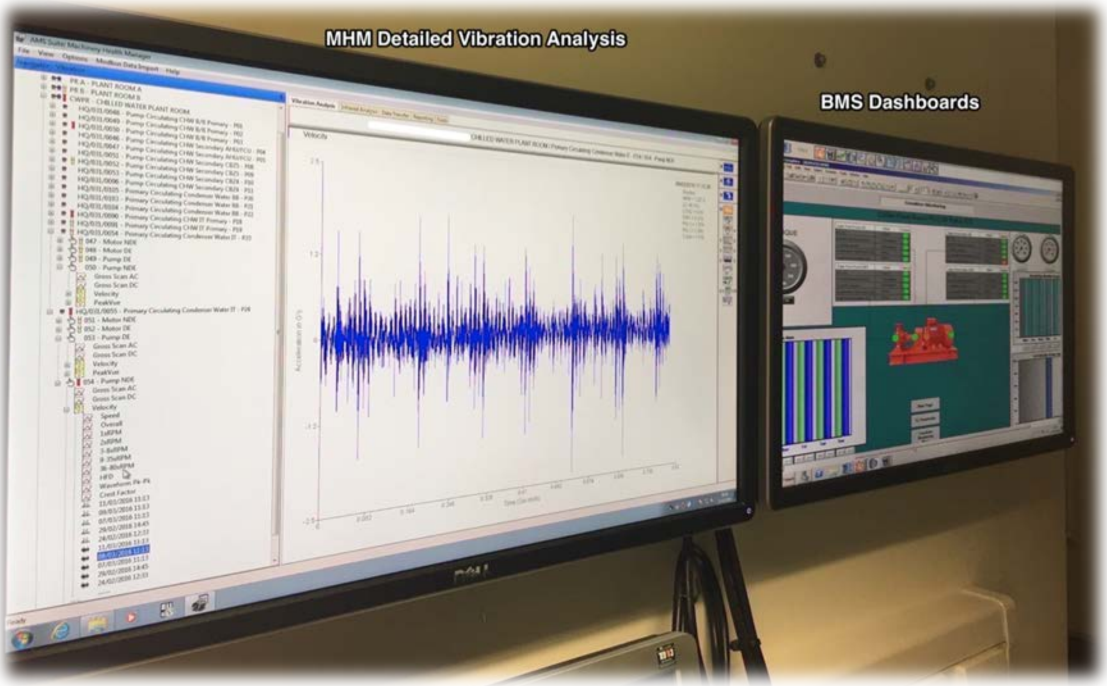


Figure 77: Dedicated wall displays visualising vibration analysis and BMS dashboards

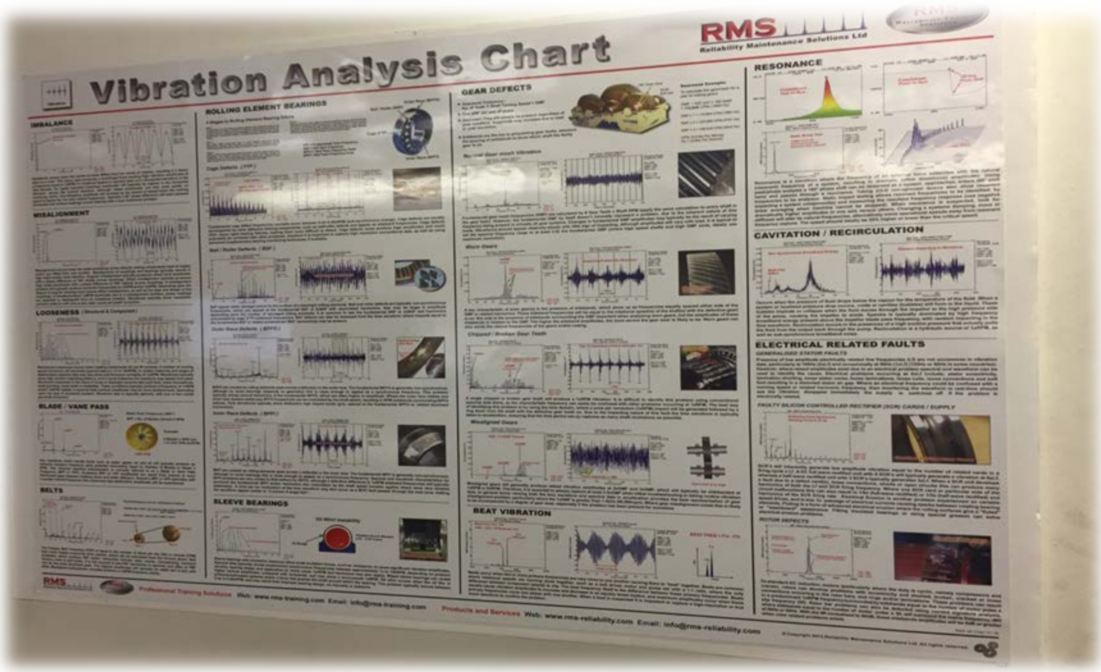


Figure 78: Vibration analysis chart with fault characteristics on wall

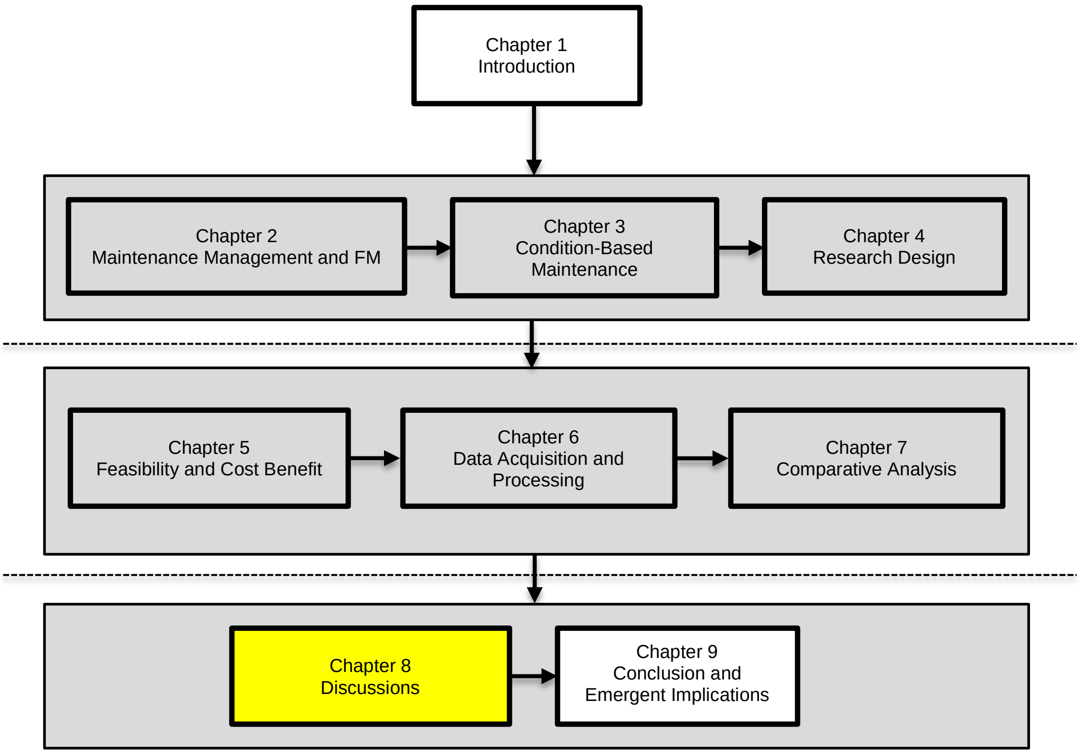
7.6 BOX 7: SUMMARY OF COMPARATIVE ANALYSIS OF RESULTS

This chapter details the comparative analysis of the research, in summary:

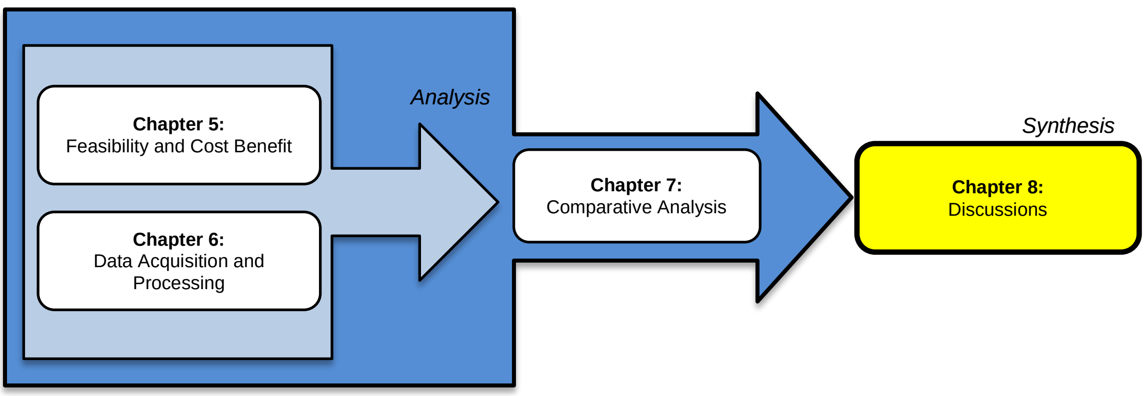
- The viable and applicable online vibration condition monitoring has complimentary effects on the existing time-based maintenance regime.
- The early detection and diagnosis of faults using online vibration analysis enables informed decision-making operationally, tactically and strategically.
- Similarly, applying condition-based data driven analysis techniques was recognised by employees to add value and it triggered a positive change of moral and attitude at all levels of the hierarchy.
- The comparative analysis relating operating hours of assets revealed that the actual operations are 30% less than scheduled and energy consumption is 35% less and therefore so is the cost which is based on consumption. However, the this difference does not consider the data which was unable to be collected due to network issues, so the actual difference may be much lower.
- The AHU fans were identified to be operating up to 35% more than the automated scheduled hours.
- There are no management approval protocols in place to govern duty and standby changes, which means some assets are having more start-ups and shutdowns, as well as operating more hours.
- Univariate and multivariate logistic regression analysis is conducted to establish the associating factors of fault occurrence: -
    - At the univariate level, all three independent variables (average temperature, average humidity and average current) were significantly associated with the occurrence of fault.
    - However, at the multivariate level, only increased average current was associated with increased probability of fault. More specifically, for every one Ampere increase of the average current, there was an 8% increase in the fault.
- Bespoke visualisation dashboards have been created through integrating the data analysis on the BMS and presenting the screens on wall mounted displays, this will allow a variety of personnel to intervene. This will enable the following benefits:
    - Informed management decision-making relating to maintenance and operations without complex data interpretations.
    - Ensure that non-technical personnel can interpret the complex data to establish fault detection and trigger maintenance actions.

The next chapter will conduct discussions through synthesizing the data analysis.

8 DISCUSSIONS



This synthesis chapter will implement the data analysis triangulation methodology in order to analyse all relevant observations from the literature review in Part A and the empirical research presented in Part B of this thesis. The observations are succinctly discussed in the context of the defined research domain (buildings maintenance management) and structured with reference to the original research objectives.



8.1 BUSINESS CASE: TECHNICAL FEASIBILITY AND ECONOMICAL JUSTIFICATION

The review of literature on maintenance management and more specifically FM in Chapter 2 highlighted the significance and complexity of maintenance in the context of FM within the built environment. In analysing the key concepts, policies and actions relating to maintenance management it emerged that whilst majority of research in the past decade has focused on CBM (the use of predictive actions) the practical application within the built environment is non-existent, consequently time-based preventive policies such as PPM are applied consistently (Chanter & Swallow 2007; Mobley 2002; RICS 2009; Pitt et al. 2006). In contrast, reviewing the general sphere of maintenance management demonstrated that the most evolved (third generation) customised maintenance concept (utilised by industries such as aviation), is an in-house developed and/or cherry picked to combine elements of preventive, predictive and proactive features that exploits the company's strengths within the specific business context (Kobbacy & Murthy 2008).

These findings led to the decision to focus this research on maintenance management in the context of FM within the built environment, and more specifically the endeavour to implement a CBM focused customised proposal, which enables informed predictive maintenance actions.

Further analysis of literature relating to the implementation of CBM techniques was undertaken in Chapter 3. This review of literature on CBM implementation most importantly emphasised that the practical implementation component is expensive (Ahmad & Kamaruddin 2012). Consequently whilst it has been demonstrated to be feasible technically in some industries (such as aviation and manufacturing), it is seldom successful economically (Koochaki et al. 2011; Jardine et al. 2006; Al-Najjar 2012).

In particular, the work of Koochaki et al. (2011) stresses that unsuccessful installation and inadequate realisation of benefits are consquent of the investment justification processes not being inclusive of operational impacts and primarily concentrating on a single asset. This is is further supported by Muchiria et al., (2009) highlighting a need for better alignment between operational and tactical requirements for justifying and implementing CBM.

As a result of such debates, it is recommended in international standard guidelines such as ISO 17359:2011 (British Standards Institution 2011) that prior to implementing CBM, a technical feasibility and cost benefit analysis is undertaken. Although the prevalent execution models discussed in the literature (i.e. Jardine et al. 2006; Veldman et al., 2011a; Shin & Jun 2015) fails to specifically stress the requirement to undertake such comprehensive activity prior to CBM data acquisition, it is believed that this process ensures attention is given to total cost and establishes accurate scales and operational indicators to measure the overall effectiveness thus increasing possibility of CBM success (British Standards Institution 2011).

Consequently, as per the first objective of this study, a comprehensive feasibility investigation was undertaken to establish the cost, savings and potential opportunities of implementing CBM technologies in buildings maintenance management. Full details of the analysis is available in Chapter 5 and relevant sections of Chapter 7, the key discussions points are drawn out and discussed below.

Whilst technically feasible (establish through specialist consultants and demonstrated in Chapter 6), the proposed solution over the life of the contract would cost in excess of two hundred thousand pounds, moreover a large part of this is an initial investment. This finding supports the claims in the literature that the implementation of CBM is an expensive venture (Jardine et al. 2006; Ahmad & Kamaruddin 2012; Al-Najjar 2012).

However, the comprehensive analysis conducted on the mixed method data collection indicates that the complete implementation of the proposed 'Customised' maintenance proposal is economically justifiable since a 386 per cent net savings opportunity is available from the total cost of implementation. Nevertheless, it is important to emphasis that a core element of this saving relates to the reduction of energy consumption (0.625 per cent decrease per year, 10 per cent in total over 16 years).

The saving attributed to energy consumptions have been estimated based on the findings presented in the literature (Rao 1993; Saidur 2010; Bachus & Custodio 2003; Beebe 1987) with the belief that efficient, fault free operations of assets provide energy savings of up to 20 per cent. However, other authors such as Al-Najjar (Al-Najjar & Alsyouf 2004; Al-Najjar 2012) stress caution on such statements and consider '*extra energy cost due to disproportional energy consumption'* to be an indirect maintenance cost that is challenging to estimate, quantify and validate.

That being said, it should be noted that currently there is no methodology available in the literature that enables indirect cost estimations (see Chapter 2). Therefore the aim of this analysis was not to support the literature claim that 20 per cent energy can be saved, but to position the proposal to indicate that even a much smaller saving opportunity (i.e. 0.625 per cent, per year) could contribute significantly towards the overall economical justification process. Furthermore, this study has statistically demonstrated the significance of energy consumption and its relationship with faults, which provides additional support that rotary building assets exhibiting faults consume higher amounts of energy. Additionally, this research has setup the platform for capturing the relevant data streams to study this specific relationship in more depth via further research.

Moreover, the findings presented in Chapter 5 indicate that in addition to the potential financial savings (CAPEX and OPEX), there are numerous tactical and operational opportunities for implementing CBM including the ability to make better informed Life Cycle and maintenance intervention decision based on data, as well as improve the quality of service through reduction in unplanned downtime.

This is comparable to the assertions made by Muchiria et al., (2009) and subsequently Koochaki et al. (2011) for a need to align the operational requirements within the initial feasbility analysis and consider CBM implementation beyond the single asset mindset. Futhermore, the mixed method research approach (which was supported by the action research platform), aided the engagement of all relevant stakeholders throughout this analysis and ensured adequate consideration was given to the key technical and commerical components at all three management level: strategic, tactical and operational (Kobbacy & Murthy 2008).

On balance, this study has demonstrated the potential cost, savings and opportunities associated with implementing CBM on building maintenance through conducting a comprehensive technical and economical feasibility analysis. The findings from this research objective support the literature position that CBM is an expensive methodology to implement in practice with substantial initial investment, which may deter companies pursuing this strategy.

Additionally and notably, the findings provide a new contribution to that opinion by revealing the potential savings and opportunities within the built environment, which can be significantly greater than the overall cost (disseminated through Amin et al., 2015).

8.2 VIABILITY AND PRACTICALITY OF ONLINE VIBRATION ANALYSIS

Following the comprehensive technical and economical feasibility analysis, the second research objective related to the practical implementation of online vibration monitoring on critical rotary building assets to establish the viability and practicality of CBM, as articulated with empirical findings in Chapter 6 and 7. Each observation will be briefly presented, discussed and contrasted against the available literature.

The first and most promising finding from this objective is that within the context of buildings asset maintenance, it is viable and practical to implement online vibration analysis to enable predictive maintenance actions.

Although no comparable research of this nature nor scale surfaced from the literature review, the generic discussions in the literature stress that such CBM techniques are usually reserved for high value, high risk assets such as aviation, aerospace (Kobbacy & Murthy 2008; Shin & Jun 2015). Moreover, the technical feasibility is documented to be the key obstacle for the lack of implementation and adoption within industry (Jardine et al. 2006; Veldman, et al. 2011a; Veldman, et al. 2011b; Ahmad & Kamaruddin 2012).

However, in relation to this study, while a couple of obstacles were experienced in this context, overall it was possible to overcome them and demonstrate the viability element (based on guidance of ISO standards).

The second encouraging finding relates to the practicality of vibration analysis and the effect it had on the existing time-based maintenance regime. Firstly, in relation to the practicality, it was demonstrated that several faults were detected, diagnosed and root cause established through analysing the online vibration data. Secondly, regarding the effects of vibration analysis on the existing time-based regime, this study demonstrated that the sole application of time-based PPM is not sufficient for detecting and diagnosing mechanical faults (such as bearing damage) thus vibration analysis has a complimentary effect (Amin & Pitt 2014).

Again, although no comparable research in this specific context is available in the literature, the generic application discussions support these findings (see research such as, Shin & Jun 2015; Mitchell & Capistrano 2007; Au-Yong et al. 2014).

Additionally, the argument presented throughout literature that vibration analysis constitutes large, complex data analysis to be undertaken by technically competent personnel, is also supported by this study (Jardine et al. 2006; Veldman, et al. 2011a; Holmberg et al. 2010; Zhen et al. 2008).

However, one instance where the findings in relation to the viability and practicality of vibration analysis appear to be limited, is the application of prognostics, which is an extensively discussed component of CBM (Jardine et al. 2006; Veldman, et al. 2011a; Tinga 2010). In the context of this study, it should be noted that prognostics was not in the original scope since the application of prognostic models require substantial quantities of data and/or experience which was unavailable prior to the implementation of this research project. Therefore, this study has set the data acquisition, data processing and decision-making platforms (as per the Jardine et al., (2006) CBM execution model) for further research to be conducted beyond the realms of fault detection and fault diagnosis, and into the new and complex domain of fault prognostics.

8.3 STATISTICAL ANALYSIS AND ASSOCIATION OF FAULT OCCURRENCE

In conjunction with the application of online vibration analysis to enable predictive actions, the third objective of this study focused on the statistical analysis of atmospheric condition data (temperature and humidity), in conjunction with energy consumption and faults detected with vibrations analysis.

The first notable observation from this objective relates the analysed operating hours and environmental conditions. This study has empirically demonstrated that the conditions (within which building assets operate) and the hours of operation can vary significantly. Yet, time-based PPM is applied on all assets universally without taking these differences into consideration.

This finding is comparable to the research presented by Labib (2004) and Tam et al. (2006), which stress that assets require bespoke PPM regimes based on individual operating parameters and original equipment manufactures who mandate overall frequency intervals may have hidden agendas.

The second observation (which was incidental), relates the duty and standby configuration of the assets. The scheduled configuration on the BMS suggested a 50:50 ratio of operation between the duty and the standby (although the data suggested that this was not always conformed).

This finding contradicts the surveyed literature, which emphasis that a 50:50 ratio is not an effective strategy, and recommends that a 90:10 ratio is operationally superior at reducing risk (Mather 2006; Reed 2006; Notes 2013). Therefore, the implications of this finding, highlights a necessity for the overall asset operations strategy to be reviewed.

The final significant finding from this objective relates the univariate and multivariate statistical analysis of fault occurrence. This study has demonstrated the association of three key variables on manifestation of faults that are detected using vibration analysis (see section 7.3.1).

Although no comparable research emerged from the literature review, both (univariate and multivariate) analyses supported the belief that faulty assets consume higher amounts of energy. Moreover, the analyses were conducted on a robust dataset acquired over a long period of time and contained operational assets of various sizes, and conditions (faulty and healthy, established using the vibration analysis), which operated in numerous environmental circumstances in the building (varying temperature and humidity condition).

8.4 MAINTENANCE MANAGEMENT DECISION-MAKING

The final component of discussion is aligned to the overall research objective and question, which relates to the impacts of implementing CBM policies on buildings maintenance management.

The first and most concerning observation from this research project, is the evidence of preventive policies (i.e. time based PPM) as the solitary maintenance strategy for buildings assets.

In comparison to the surveyed literature, this is concerning on two facets. Firstly, as highlighted by the works of Kobbacy & Murthy (2008) and Pintelon & Parodi-herz (2008), maintenance management policies have evolved over the last fifty years (see Section 2.2). Yet, the practices observed within this case study are comparable to maintenance practices commonly implemented in the 1970s, where there was a concern of over-maintenance (also highlighted by maintenance engineers in this study). Secondly, the building maintenance domain may find it challenging to attract and retain the future ‘technology-savvy’ breed of engineers, who will want career diversification and development aligned to the technological (r)evolutions, as highlighted in this study.

The second and more promising finding relates to the added value of CBM that was demonstrated at all three maintenance management levels (operational, tactical and strategic), to enable informed decision-making.

In comparison to literature, although this is recognised to be necessary (Kobbacy & Murthy 2008), the convoluted sphere of building maintenance management has limited innovative tools available to aid management decision-making (Pitt et al. 2006; Goyal & Pitt 2007).

However, it is important to stress that the added value was only observed once the complex CBM data was competently analysed and interpretations simplified to the relevant management levels, as demonstrated by the management tool developed in this study.

Nevertheless, whilst the justifications, savings, opportunities and feasibility of business process integration has been demonstrated in this study, the requirement for competent skillsets for interpretations in conjunction with the initial investment obligation may continue to be the key barrier for industry wide adoption of CBM policies for predictive buildings maintenance management strategies.

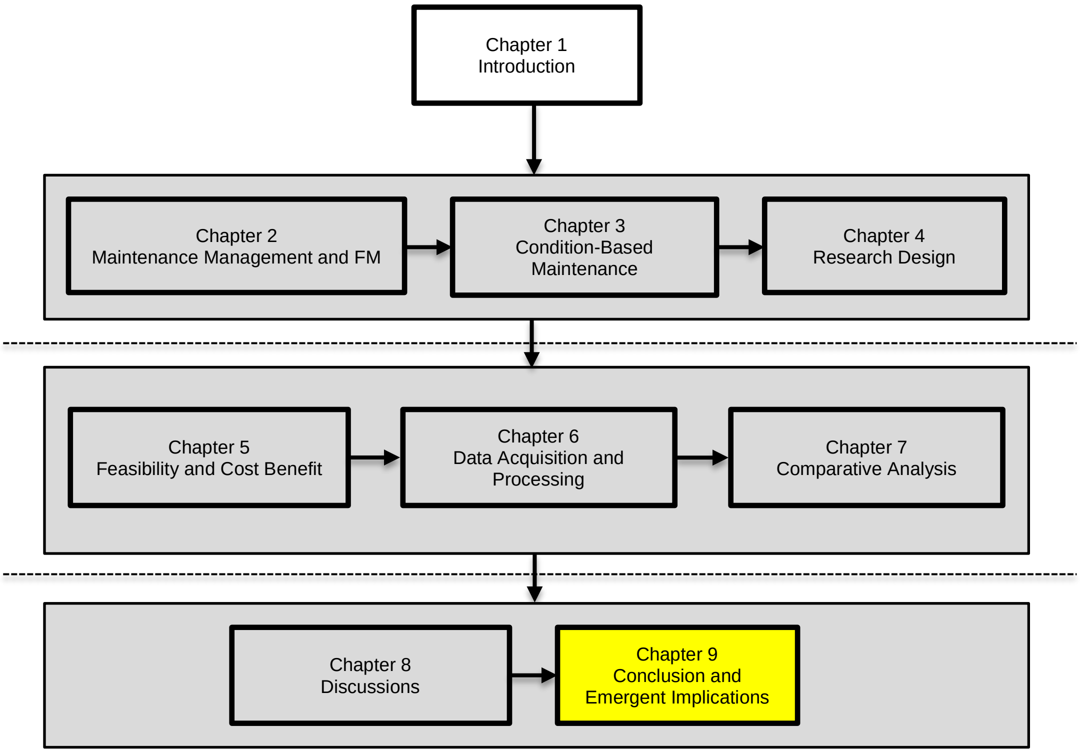
8.5 BOX 8: SUMMARY OF DISCUSSIONS

This chapter implemented data analysis triangulation to synthesis the findings in alignment with the research objectives, in summary:

- As per literature and ISO recommendations the first objective of this study involved the technical feasibility and economical justification:
  - There is a gap in the literature relating to the cost, savings and opportunities of implementing CBM policies within the context of building maintenance management.
  - This study has identified support for various literatures suggesting CBM implementation is an expensive venture. However, in contrast, in the context of this research, the proposed 'Customised' framework is empirically quantified to deliver significant economical opportunities.
  - The potential economical scale of energy savings is emphasised and whilst certain literatures indicate large reductions, this study demonstrates that a small reduction in this context can deliver large saving opportunities.
  - The tactical and operational management opportunities of CBM identified in this study is further supported by relevant literature comparisons.
- Second, the viability and practicality of online vibration analysis is explored:
  - Whilst no comparable literature is available, this study demonstrated that large-scale online vibration condition monitoring and data analysis is practical and viable in this domain. Therefore, such CBM technologies should not be reserved for high value, high risk asset industries as commonly discussed in the literature.
  - Although prognostics was not in the scope of this research, this study has set the data acquisition foundations for this complex research stream to be initiated.
- Third, the association of fault occurrence is statistically analysed through various datasets:
  - Asset operating hours and operating conditions vary, which support literature stance that bespoke maintenance regimes are necessary.
  - The statistical fault association quantified that rotary buildings assets exhibiting faults consume more energy; again no comparable literature is available.
- Fourth, maintenance management decision-making is discussed:
  - Maintenance practices identified in this case study highlights several concerns and has commonalities with that of 1970s, rather than the most evolved.
  - Proposed CBM Concept demonstrated management added value for buildings.

The next chapter will highlight the most relevant conclusions and emergent implications of this research.

9 CONCLUSION AND EMERGENT IMPLICATIONS



This last chapter emphasises the most significant facets of this research on CBM in relation to building maintenance management. Alongside the most relevant conclusions, the emergent implications, with research limitations, are described and a body of future works is proposed. Finally, the original contribution to knowledge is outlined and the activities used to disseminate the findings highlighted.

9.1 RESEARCH BACKGROUND

The review of literature in the context of maintenance management indicated the significant role of maintenance towards ensuring availability, reliability and safety within a wide range of industry sectors such as aviation, processing, manufacturing, military and the built environment. Moreover, the sphere of maintenance appears to have evolved over the last fifty years, as a result it is now considered to be a young, dynamic and complex management science that intertwines a variety of disciplines and demands recognition at all levels of the organisation (i.e. strategic, tactical and operational).

However, the necessity to harmonise multidisciplinary operations, technologies and logistic support often convolutes the context of maintenance management, and generates many challenges (e.g. technical and commercial) that require organisations to contemplate and adapt in conjunction with core business goals. Therefore, the successful adaption and integration of core maintenance components requires the deployment and embracing of most desirable maintenance concepts (task and rules in-line with business goals), which can epicentre key issues and challenges (e.g. optimisation, policies, actions) that subsequently impact the core business objectives.

Nevertheless, some industries (e.g. aviation and military) appear to be dealing with such challenges better than others (i.e. built environment) at embracing the evolved concepts that are being accelerated by the technological (r)evolutions. Therefore, while the pioneers are implementing customised third generation maintenance concepts that are not only developed to exploit the organisation's strengths and weakness within the specific context, but also integrates maintenance policies, strategies and action elements that are most desirable (i.e. 'cherry-picked' combination of corrective, preventive and predictive), others such as the built environment (i.e. building maintenance) continue to perceive maintenance as a 'technical matter' and practice second generation concepts that not only fails to embrace recent technologies but also demands exhaustive resources to deliver actions which may be unnecessary.

Consequently, this industry sponsored research sought to demonstrate the practicality, viability and impacts of implementing a customised third generation maintenance concept that enables online CBM and statistical data analysis to support and inform building maintenance management decision-making. The most significant conclusions of this large-scale, unprecedented research project are provided in the following section.

9.2 MOST RELEVANT CONCLUSIONS OF THE RESEARCH

This research was conducted within a large, operational public sector building in the UK that is part of a long-term PFI contract with a maintenance budget of circa £4 million per annum. More specifically, the research was focused on critical rotary HVAC system components namely, 83 individual motors, pumps and AHU supply and extract fans. Such rotating assets are prevalent within the built environment and form the foundation of building services engineering and building maintenance management protocols, which promotes relatability and transferability of this study.

The empirical findings from this study relate to the main research questions and objectives, which set out to enhance the background research (see Amin & Pitt, 2014) and ascertain the impacts of implementing online CBM policies and statistical data analysis in building maintenance context. In exploring the main research question three sub-questions were developed and investigated.

First, the cost, savings and opportunities of implementing CBM were established through a comprehensive technical feasibility and cost benefit analysis. The survey of literature relating to maintenance management highlighted that CBM appeared to be reserved for high risk and high value assets such as military, aeronautics industries and critical manufacturing plant. Moreover, CBM is recognised as an expensive maintenance strategy that rarely provides the economical justifications. Therefore, this investigation implemented an exclusive mixed-method data collection methodology that was further supported by the action research platform of monthly EngD board meetings (involving academics and professionals) to ensure collective and iterative scrutiny of the analysis and findings. Moreover, to enable the comparative analysis to identify the savings and opportunities, the relevant condition monitoring data acquisition costs were acquired through three specialist external consultants and the most economical option was used for the financial justification analysis.

The comparative financial analysis was conducted based on the existing time-based maintenance policy and a proposed concept that was inclusive of CBM polices enabling predictive and proactive maintenance actions. Furthermore, the analysis considered the most significant business impacts in respect to the application of condition monitoring, OPEX and CAPEX over the total remaining life of the PFI contract (sixteen-years).

The findings indicate that the proposed third-generation maintenance solution, which amalgamates time-based actions with CBM policies, has the potential to provide an OPEX saving opportunity of £541,464.14 and a CAPEX savings opportunity of £250,000. Additionally, it would generate be a variety of managerial and service operational benefits and opportunities that are challenging to quantify at this stage.
These unquantifiable benefits and opportunities relate to risk management, reduction in asset downtime, service quality improvements and informed asset life cycle decision-making.

Therefore, using these findings, a business case for investment to support the implementation of the proposed solution was developed, submitted and approved by the relevant Boards of Directors.

Second, following the investment approval, a renowned commercial off the shelf CBM solution was implemented through a dedicated specialist project team to enable online vibration condition monitoring and data analysis. The installation involved extensive hardware and software configuration on assets within an operational environment, in contrast to literature, which predominantly discusses laboratory setups. The analysis of complex vibration data to establish asset health conditions was undertaken with the guidance of specialist consultants and in parallel with most relevant international standards.

Third, the association of relevant variables were tested to establish their relationship and impact on the occurrence of faults. To achieve this temperature and humidity sensors were installed in plantrooms to acquire data for the atmospheric environments within which the assets operate. Additionally, the energy consumption and operations data were extracted from the existing buildings management system (BMS). The acquisition, processing and analysis of this extensive dataset provided three notable findings to be extracted:

> Firstly, the plantroom temperature and humidity within which buildings assets operate indicates a significant variance across the internal roof and basement locations investigated. For example, Plantroom A (basement) appeared to demonstrate consistently high temperatures and low humidity, including several occasions of exceeding 50°C and an annual average of 46.5°C and 19.4%.
>
> Secondly, in relation to the energy consumption and operations, the findings also suggest a significant variance of operations between the assets. For example, from the roof locations the highest operating asset was 91 per cent more hours than the lowest, whilst from the basement location the difference was 81 per cent. Moreover, the automated 50:50 duty and standby operations mandated on the BMS was exceeded by 10-16 per cent.
>
> Lastly, the above dataset was processed and the mean temperature, humidity and current consumptions were used as independent variables within a univariate and multivariate logistic regression model that was implemented to establish statistical association based on a dichotomous dependent fault variable (established through vibration analysis). The findings from this analysis indicate that at the univariate level, all three independent variables were significantly associated with the occurrence of fault. In contrast and more significantly, at the multivariate level, only current was associated with the fault occurrence. More specifically, for every one Ampere current increase, there was an eight per cent increase in the fault.

Therefore, in relation to the overall research question, the combined empirical findings from this study indicate that implementing a CBM policy within a buildings maintenance context is not only practical and viable, but also has the potential to provide numerous opportunities that subsequently have significantly positive impacts on the maintenance management protocols.

Furthermore, although the large-scale online vibration data acquisition demonstrated in this study requires complicated setup and installation process that appeared to be time-consuming (e.g. two months), and a few obstacles were encountered relating to variable speed assets and operating parameters to trigger data collection, overall the implementation within an operational buildings context was demonstrated to be successful and the positive management impacts highlighted through early fault detection and diagnosis. Moreover, the ability to evidence asset condition and inform decision-making was considered valuable throughout all management levels including operational, tactical and strategic.

Additionally, this study has confirmed various literature postures that CBM generates large-scale and complex datasets, which require specialist expertise to manage and analyse. Nevertheless, the robust I.T network infrastructures that commonly exist within buildings aid the CBM data collection and visualisation. For instance, in this study the data from the online vibration monitoring and analysis solution was innovatively integrated into the existing BMS network and bespoke data fusion visualisation dashboards were developed to enable informed maintenance management decision-making without convoluted vibration data analysis.

More significantly, this study has demonstrated that time-based PPM, which is prevalently practiced in buildings maintenance management, is insufficient at detecting and eliminating mechanical faults associated with critical rotating assets. For example, whilst 91 per cent of assets in this study were analysed to be in ‘good operating condition’ in relation to the international standard condition thresholds, 9 per cent were identified to have some form a fault, which were not detected by the time-based PPM actions. Moreover, the small proportion of fault detection in this project may be consequent of the background research project conducted using remote hand-held vibration and Shock Pulse Method condition monitoring, which detected an initial 48 per cent of assets demonstrating some form of faults in accordance with international standard guidelines (these faults were rectified as part of the background study).

Furthermore, the findings in relation to the environmental conditions and operations variances highlight a need for buildings managers to contemplate utilising data analysis to reinforce asset operation mandates and adapt maintenance policies and actions to reflect individual asset operations and plantroom environment conditions, since such variables could impact asset reliability, service quality and energy consumption.

On balance, whilst the initial investment remains substantial, this study has demonstrated numerous motivations and opportunities for building maintenance managers to adopt a third-generation RCM-customised maintenance strategy that embraces and amalgamates CBM and time-based policies to delivery value at all management levels.

9.3 EMERGENT IMPLICATIONS

This section focuses on the relevant implications that can be extracted from the empirical comparative research in Chapter 7 and the discussions in Chapter 8. Four emergent implications are identified and briefly described as follows.

9.3.1 BUSINESS CASE AND JUSTIFICATION FOR INNOVATION

In the complex context of buildings maintenance management and similar to other lean business models within the built environment, there is a continuous requirement to improve business processes through operational efficiencies and innovations. However, it is usually challenging to demonstrate the technical feasibility and deliver a persuasive business case justification, consequently this specific field of the built environment has been deprived of innovative contributions to the service delivery (RICS 2009). Therefore, components of comprehensive technical and economical feasibility analysis methodology (implemented in this study) should be considered by organisations to demonstrate the technical and economical business case for implementing innovative policies such as CBM (i.e. methodology to justify similar programmes).

9.3.2 IMPACT ON BUILDING SUPPLY CHAIN MANAGEMENT

The extensive application and recommendation of time-based PPM in isolation has been empirically evidenced to be inadequate at completely eradicating faults on buildings assets. Therefore, the entire building supply chain (manufacturers, developers, insurers and managers) should consider adopting some form of CBM technologies such as vibration analysis to compliment their existing time-based maintenance regimes. The methodologies, viability and practicality demonstrated in this study can be used as a platform to engage with relevant stakeholders and consider a joint effort towards implementing additional and/or alternative maintenance policies. Moreover, engagement with building asset manufacturers to consider predictive maintainability (e.g. ingrain sensors) at the asset design and development stage could reduce cost of retrospective installations and support wider industry synthesis

9.3.3 OPERATIONAL DATA ANALYSIS

The findings in relation to the operations (scheduled and actual), energy consumption and duty standby configuration were accomplished through analysing existing parameters associated with the assets. These parameters are easily accessible to most building managers via the BMS and do not require investment nor additional sensor installation. Therefore, as demonstrated in this study, conducting such data analysis would enable greater management insight not only in relation to the operations and lifecycle replacement planning, but also the continuous energy consumption patterns, which could be used to statistically trend and detect faults based on unusual consumption. This notion of 'energy consumption based fault detection' could be implemented as an introductory and cost effective path to CBM policies.

9.3.4 MAINTENANCE CONTRACT AND PROCUREMENT CHANGES

The findings in relation to the inadequacies of time-based PPM parallel with the viability and practicality of online vibration analysis to determine the conditions of building assets and enable informed decision-making, reiterates the need for CBM policies to be inclusive within the maintenance management strategies. This should motivate relevant stakeholders (such as government agencies, construction and FM companies) to consider policy and/or contractual changes at the earliest possible stage i.e. design and/or procurement of buildings.

This is particularly relevant for PFI contracts involving high risk buildings (such as hospitals and defence) since the lengthy concession periods not only require continuous evidence of adequate maintenance and asset health, but more significantly usually include an allocated CAPEX budget for lifecycle replacements throughout the contractual period. Yet, as demonstrated in this study, such considerable financial decisions (e.g. bearing replacements) may be undertaken based on hypothetical configurations, manufacturers generic test environment recommendations and/or operational scenarios that does not completely reflect the reality in practice. Additionally, PFI contracts should consider the contractual positions of potential financial opportunities attributed to energy savings from efficient operation of assets and appropriate agreements between the relevant stakeholders (e.g. gain-share agreement).

9.4 RESEARCH LIMITATIONS

The numerous emergent implications identified and discussed in section 9.3 should be considered in conjunction with the following key limitations associated with this research.

9.4.1 ROTATING MACHINERY

This study focuses solely on rotating machinery in buildings therefore, although the investigated assets (pumps, fans, motors) are all prevalent within the built environment, the implications are limited to a minority of the equipment that requires maintenance to be implemented within this domain.

9.4.2 SINGLE CASE AND SOCIAL STRUCTURE

The research is implemented on a single case study. Therefore, the practical managements impacts and the technical practicality and viability of implementing a customized third generation maintenance concept is limited to the overall attributes and constraints associated with such environment, e.g. PFI, public sector defense site. Moreover, as a result of the single case study focus, the research is limited to fixed social structures within that case therefore the implications may be challenging to transfer to other buildings.

9.4.3 ACTION RESEARCH PLATFORM

The research was conducted using multi-strand mixed (qualitative and quantitative) methods based on an action research platform that consisted of a unique collaborative Engineering Doctorate (EngD) partnership between industry and academia, such partnerships may be challenging to replicate within the FM domain. Additionally, due to the engineering focus, the data collection instrumentations were biased towards the quantitative methods, than the qualitative methods.

9.5 FUTURE RESEARCH DIRECTIONS

Amalgamating the research findings from this study with the discussions and the emergent implications produces numerous interesting directions for future research. Specifically, five research directions have been identified to continue the exploration beyond the established issues and platforms discussed in study.

It should be noted that this study, which has investigated an unprecedented practical implementation within an operational buildings environment, has become a pioneering example for further research to be undertaken by the stakeholders within the specific domain of CBM applications in the context of buildings maintenance management. Consequently, the sponsoring company and researcher, in collaboration with other organizations, have already initiated the first research direction described below.

9.5.1 ARTIFICIAL INTELLIGENCE AND PROGNOSTICS MODELLING IN PRACTICE

The beneficial applications for artificial intelligence (AI) and machine learning algorithms are extensively discussed in the literature from a conceptual viewpoint mostly using test rig datasets. Similarly, the data driven prognostics relating to the prediction of remaining useful life of assets has been demonstrated to be invaluable in some industries (i.e. aviation).

Nevertheless, such notions have not yet been explored within the built environment. Therefore, the data acquisition and processing platforms established by this study, is being used as the foundation for research to be undertaken in this unique field. More specifically, the ongoing data collection from this study is being utilised for testing AI based Neural Network models with the aim of deploying prognostics modeling on buildings maintenance management.

9.5.2 ENERGY SAVING MODELLING AND IMPLEMENTATIONS

As recognised in this study, energy consumption analysis and modelling can not only provide financial savings through efficient operations and aid sustainability agendas, but also enable fault detection. Therefore, it is highly recommended to conduct further research in this area with specific attention on developing operational energy consumption scales and thresholds to assist operations and maintenance management decision-making.

9.5.3 INEXPENSIVE AND WIRELESS CBM

As identified in this study and discussed by numerous literature, cost can be one of the barriers for retrospectively installing tools and/or sensors on assets to enable CBM predictive actions. However, the viability and practicality demonstrated in this study was achieved using industry best practice hardware and software solutions (e.g. accelerometers, vibration analysis software) that were in compliance with British and International standards. Moreover, the installation demonstrated in this study was completely hardwired, excluding hardware with wireless capabilities (due to building security restrictions). Consequently, such features and confinements may have inflated the overall implementation cost detailed in this study.

Therefore, further research is recommended to establish the minimum hardware and software requirements (e.g. lower technical specification and reduced capability configurations) for the viability and practicality of inexpensive implementation. Additionally, the application of wireless accelerometers and data collectors should be considered towards such research project designs to determine the wireless feasibility within building plantroom environments.

9.5.4 CBM INTEGRATION WITH BUILDING INFORMATION MODELLING (BIM)

Although a reasonable new concept, BIM has quickly become the most widely discussed and utilised tool across the entire construction industry with various degrees of application and integration throughout the building life cycle. The fundamental principle of BIM has data at the core of the 3D digital representation of physical and functional characteristics of a building. Comparably, as demonstrated in this study, CBM has the potential to generate copious amounts of data, which could be invaluable to collaborative integrated buildings operations and FM.

Therefore, parallel with the UK Government mandate for all public constructions projects to achieve BIM Maturity Level 2, further research is recommended in relation to buildings maintenance management and the integration of asset condition and maintenance data into the 3D visualisation.

9.5.5 CIBSE GUIDELINES

Whilst numerous international standards are available for CBM guidance, there appears to be limited coverage specifically within buildings services guidelines such as CIBSE Guide M. Therefore, further research, collaboration and engagement is recommended to generate greater awareness of opportunities within the buildings services engineering communities with the goal of developing a explicit set of practical CBM implementation guidelines.

9.6 CONTRIBUTION TO KNOWLEDGE

By achieving the main research aim, this thesis has provided six notable contributions to knowledge within the contexts of maintenance management and the built environment.

9.6.1 BUSINESS CASE MODEL

Comprehensively established cost, savings and opportunities of implementing a customised third generation RCM maintenance concept that is aligned to FM business needs and inclusive of predictive maintenance actions. Rational for the model is based on existing cost/benefit requirements available in international standards but has been developed for the PFI buildings maintenance context through the action research platform of iterative stakeholder scrutiny. Moreover, the results of the analysis were validated to formulate the investment proposals and successfully acquire industry funding of approximately £250,000 to implement the proposed strategy. Therefore, the technical and economical justification model developed in Chapter 5 is transferable to other PFI cases in order to enable similar innovation rationale for better building maintenance management.

9.6.2 CBM FOR BUILDING MAINTENANCE MANAGEMENT

The study has demonstrated operational viability and practicality of implementing CBM through online vibration analysis. Beyond the solitary use of specialist expensive condition monitoring solutions, this study has highlighted the significance and potential of conducting data analysis on the wealth of event data (from CAFM) and operational data (from BMS) that is effortlessly available in buildings maintenance management. More significantly, the findings from this study emphasise the inadequacies associated with exclusively applying time-based PPM and the inevitability to support and compliment time-based actions with condition monitoring datasets.

9.6.3 STATISTICAL ASSOCIATION OF FAULT

The univariate and multivariate statistical analysis conducted in this study demonstrated the potential practicality of the available datasets. Moreover, using this dataset the study has quantified the statistical association between vibration induced faults (that can be detected and diagnosed through online condition monitoring) and energy consumption. Therefore, the established probability association can be utilised as an inexpensive mechanism to trigger and/or inform maintenance actions exclusively based on excessive energy consumptions.

9.6.4 VIBRATION DATA FUSION WITH BUILDING MANAGEMENT SYSTEM (BMS)

Significant amounts of individual systems and data are available within buildings and CBM contributes and complicates this dataset further. For example, buildings services management and engineering is commonly conducted within various software systems that support the existing core BMS systems, which are familiar to maintenance management personnel. Meanwhile, implementation of a new online vibration condition monitoring solution provides users yet another system for end-users to learn.

Therefore, to promote the success of CBM application and accommodate non-technical user understanding of complex systems and associated data, this study has demonstrated a novel data integration process. Using existing building IT network protocols (i.e. BACNET and MODBUS) in conjunction with PXC36 Compact Series Controller, this study has successfully unified large-scale vibration datasets with operation and energy consumption datasets on a simultaneous amalgamation within the existing core BMS.

9.6.5 INTEGRATED MANAGEMENT VISUALISATION TOOL

This study has developed and demonstrated the application of a management data visualisation tool, which is integrated with the existing core system infrastructure (i.e. BMS network) and amalgamates real-time asset condition monitoring with operations and energy consumption. Moreover, the various dashboards enable non-technical building services personnel to interpret the complex condition monitoring data and inform strategic operations and/or maintenance management decision-making.

9.6.6 EMPIRICAL MANAGEMENT POSITION OF CBM

This study has contributed towards filling the significant gap in maintenance management literature. As highlighted by the works of Kobbacy & Murthy (2008), Pintelon & Parodi-herz (2008) and Garg & Deshmukh (2006), the existing body of knowledge focused on research relating to specific actions or policies at the tactical and operational level. This has created a shortcoming in ensuring alignment of overall maintenance strategy to the business strategy, consequently there is a lack of industry application and optimisation of the most evolved strategies. Furthermore, in the specific area of CBM and third-generation concepts, no research was available to document the management potential and impact within building maintenance. As a result, the realities presented in empirical literatures fail to reflect the core organizational business goals and objectives.

Therefore this research has demonstrated the added value of implementing a customised CBM concept through an innovative action research platform, which not only enabled the maintenance strategy to be aligned with the corporate strategy, but also supported the economical and technical components to be harmonised with the core business objectives (the necessity for this is stressed by Kobbacy & Murthy, 2008). Furthermore, it highlighted deficiencies with the existing execution models available in the literature (e.g. Jardine, et al. (2006), Veldman, et al., (2011a) and Ahmad and Kamaruddin (2012)), in this respect the guidance available in international standards are far more robust. Nevertheless, the business system and process integration element of this research (also not documented in the literature) highlighted challenges with interpreting complex datasets, however it was possible to combat this through the development of bespoke data visualisation dashboards to integrate the new processes into existing systems.

9.7 Dissemination Activities

Although this is an industry collaboration research project, within the academic community this study has been discussed and disseminated through a combination of peer-reviewed journal articles, conference presentations and peer-reviewed conference proceedings. For example, targeting the specific domain of the research, the findings from the technical feasibility and cost benefit analysis (chapter five) were presented to the academic and research track audience at the International Facilities Management Association (IFMA) Conference (2015).
Moreover, further publications via journal articles from this research project are proposed in order to disperse the comprehensive findings, conclusions and recommendations from this project, this will include content presented in chapters six, seven, eight and nine.

Additionally, one of the fundamental goals of action research projects such as this is to bridge the gap between academia and industry (as discussed in the research design). Therefore, in conjunction with the dissemination activities within the academic community, research of this nature requires operational promulgation within the collaborated industry. This was logically considered during the initial research design. Consequently, it was necessary for the researcher to not only be completely immersed within the research environment thus access operational, tactical and strategic levels of communication, but also to invite various professionals of significant role from industry to attend the EngD Board meetings in order to contribute their experience and intellectual insights to the project.

Therefore, throughout the study the findings of the research were communicated to numerous strategic level boards of directors and significant industry individuals. For example, the findings of the technical feasibility and cost benefit analysis (Chapter 5) were used by the researcher as the foundations to not only develop the board of directors business case proposals, but also to successfully acquire funding in excess of £250,000 in order to implement the proposed solution.

9.8 BOX 9: SUMMARY OF CONCLUSION AND EMERGENT IMPLICATIONS

This chapter details the conclusions and emergent implications for the research, in summary:

- The research sought to demonstrate the practicality, viability and impacts of implementing a customised third generation maintenance concept that enables online CBM and statistical data analysis to support and inform building maintenance management decision-making. The most relevant conclusions indicate that:
    - Although the initial investment costs can be high, the subsequent savings and opportunities are substantial.
    - The implementation of an industry renowned CBM solution through a dedicated project team demonstrated the viability. Moreover, the numerous positive impacts witnessed at all three management levels following implementation highlighted the practicality of such technology and data focused maintenance strategy.
- The comprehensive statistical analysis conducted on the quantitative datasets indicated that the conditions within which assets operate vary significantly, the operations strategy is not in alignment with the existing maintenance strategy and assets operating with a fault consume higher amounts of energy.
- This study has demonstrated that time-based PPM, which is prevalently practiced in buildings maintenance management, is insufficient at detecting and eliminating mechanical faults associated with critical rotating assets.
- There are four emergent implications identified:
    - Business case and justification for similar innovation investment
    - The impact of such innovations on the building supply chain management
    - The beneficial impact and effect of operational data analysis
    - The consideration necessary towards future maintenance contracts and procurements, particularly for PFI.
- Five future research directions are provided, namely:
    - Artificial intelligence and prognostics modelling in practice
    - Energy saving modelling and implementations
    - Inexpensive and wireless CBM development
    - CBM integration with Building Information Modelling (BIM)
    - Creation of CIBSE Guidance specially for the built environment
- Finally, six notable contributions to knowledge are presented in the contexts of maintenance management and the built environment.

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11 APPENDICES

11.1 APPENDIX A: ASSET DATA

11.1.1 ASSET: EVENT DATA OVERVIEW

	Area	Asset Type	No.	Fault/Breakdown History and Notes
1	Plantroom A	Primary Constant Temperature	P01A	No breakdowns or notes
2	Plantroom A	Primary Constant Temperature	P01B	No breakdowns or notes
3	Plantroom A	Secondary Constant Temperature	P05A	11/10/2012 - Replace faulty inverter
4	Plantroom A	Secondary Constant Temperature	P05B	16/10/2012 - Replace faulty inverter
5	Plantroom B	Primary Constant Temperature	P01A	No breakdowns or notes
6	Plantroom B	Primary Constant Temperature	P01B	05/10/2011 - Replace inverter
7	Plantroom B	Secondary Constant Temperature	P04A	No breakdowns or notes
8	Plantroom B	Secondary Constant Temperature	P04B	No breakdowns or notes
9	Chilled Water Plantroom	Primary Chilled Water	P01	No breakdowns or notes
10	Chilled Water Plantroom	Primary Chilled Water	P02	No breakdowns or notes
11	Chilled Water Plantroom	Primary Chilled Water	P03	No breakdowns or notes
12	Chilled Water Plantroom	Secondary Chilled Water	P08	No breakdowns or notes
13	Chilled Water Plantroom	Secondary Chilled Water	P09	No breakdowns or notes
14	Chilled Water Plantroom	Secondary Chilled Water	P10	No breakdowns or notes
15	Chilled Water Plantroom	Secondary Chilled Water	P11	No breakdowns or notes
16	Chilled Water Plantroom	Primary Chilled Water	P18	No breakdowns or notes
17	Chilled Water Plantroom	Primary Chilled Water	P19	No breakdowns or notes
18	Chilled Water Plantroom	Primary Condenser Water	P23	No breakdowns or notes
19	Chilled Water Plantroom	Primary Condenser Water	P24	26/05/2010 - leak from mechanical seal
20	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P05	24/05/2011 - Strainers cleaned
21	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P06	24/05/2011 - Strainers cleaned
22	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P07	24/05/2011 - Strainers cleaned
23	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P08	24/05/2011 - Strainers cleaned
24	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P01	24/05/2011 - Strainers cleaned
25	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P02	No breakdowns or notes
26	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P03	09/06/2011 - Strainers cleaned
27	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P04	06/08/2012 - Faulty/replace inverter
28	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P09	No breakdowns or notes
29	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P10	No breakdowns or notes
30	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P11	No breakdowns or notes
31	9th Floor Roof Chilled Water	Cooling Tower Condenser Water	P12	No breakdowns or notes

11.1.2 ASSET: DATA COLLECTION AND OPERATIONS SCHEDULE

	OPS_ID	Location	Asset_description	Asset_No.	kW	Vibration	Energy	Ops	Temp	Hum	Changeover	Change Day	Change Time	Change Sequence	Hours of Operations
	PLA P01A	Plantroom A	Primary Constant Temperature Pump	P01A	18.5	Yes	Yes	Yes	Yes	Yes	Daily	Everyday	01:00	Duty/Standby	24 Hours
	PLA P01B	Plantroom A	Primary Constant Temperature Pump	P01B	18.5	Yes	Yes	Yes	Yes	Yes					
	PLA P05A	Plantroom A	Secondary Constant Temperature Pump	P05A	30	Yes	Yes	Yes	Yes	Yes	Daily	Everyday	01:00	Duty/Standby	24 Hours
	PLA P05B	Plantroom A	Secondary Constant Temperature Pump	P05B	30	Yes	Yes	Yes	Yes	Yes					
	PLB P01A	Plantroom B	Primary Constant Temperature Pump	P01A	11	Yes	Yes	Yes	Yes	Yes	Daily	Everyday	01:00	Duty/Standby	24 Hours
	PLB P01B	Plantroom B	Primary Constant Temperature Pump	P01B	11	Yes	Yes	Yes	Yes	Yes					
	PLB P04A	Plantroom B	Secondary Constant Temperature Pump	P04A	18.5	Yes	Yes	Yes	Yes	Yes	Daily	Everyday	01:00	Duty/Standby	24 Hours
	PLB P04B	Plantroom B	Secondary Constant Temperature Pump	P04B	18.5	Yes	Yes	Yes	Yes	Yes					
	CHW P01	Plantroom Chiller	Primary Chilled Water Pump	P01	55	Yes	Yes	Yes	Yes	Yes	Daily	Everyday	Unknown	1-2-3 / 2-3-1 / 3-1-2	24 Hours
	CHW P02	Plantroom Chiller	Primary Chilled Water Pump	P02	55	Yes	Yes	Yes	Yes	Yes					
	CHW P03	Plantroom Chiller	Primary Chilled Water Pump	P03	55	Yes	Yes	Yes	Yes	Yes					
	NO OPS	Plantroom Chiller	Secondary Chilled Water Pump	P04	160	Yes	No	No	Yes	Yes	Weekly	MON	09:00	Duty/Standby	12 Hours
	NO OPS	Plantroom Chiller	Secondary Chilled Water Pump	P05	160	Yes	Yes	Yes	Yes	Yes					
	CHW P08	Plantroom Chiller	Secondary Chilled Water Pump	P08	18.5	Yes	Yes	Yes	Yes	Yes	Weekly	MON	09:00	Duty/Standby	12 Hours
	CHW P09	Plantroom Chiller	Secondary Chilled Water Pump	P09	18.5	Yes	Yes	Yes	Yes	Yes					
	CHW P10	Plantroom Chiller	Secondary Chilled Water Pump	P10	37	Yes	Yes	Yes	Yes	Yes	Weekly	MON	09:00	Duty/Standby	12 Hours
	CHW P11	Plantroom Chiller	Secondary Chilled Water Pump	P11	37	Yes	Yes	Yes	Yes	Yes					
	NO OPS	Plantroom Chiller	Primary Condenser Water Pump	P20	132	Yes	No	No	Yes	Yes	Daily	Everyday	Unknown	20-21-22 / 21-22-20 / 22-20-21	12 Hours
	NO OPS	Plantroom Chiller	Primary Condenser Water Pump	P21	132	Yes	No	No	Yes	Yes					
	NO OPS	Plantroom Chiller	Primary Condenser Water Pump	P22	132	Yes	No	No	Yes	Yes					
	CHW P18	Plantroom Chiller	Primary Chilled Water Pump	P18	55	Yes	Yes	Yes	Yes	Yes	Weekly	MON	11:00	Duty/Standby	24 Hours
	CHW P19	Plantroom Chiller	Primary Chilled Water Pump	P19	55	Yes	Yes	Yes	Yes	Yes					
	CHW P23	Plantroom Chiller	Primary Condenser Water Pump	P23	45	Yes	Yes	Yes	Yes	Yes	Weekly	MON	11:15	Duty/Standby	24 Hours
	CHW P24	Plantroom Chiller	Primary Condenser Water Pump	P24	45	Yes	Yes	Yes	Yes	Yes					

	OPS_ID	Location	Asset_description	Asset_No.	kW	Vibration	Energy	Ops	Temp	Hum	Changeover	Change Day	Change Time	Change Sequence	Hours of Operations
	CT01 P05	Plantroom Roof	Cooling Tower Condenser Water Pump	P05	37	Yes	Yes	Yes	Yes	Yes	Daily	Everyday	01:00	Duty/Standby	12 Hours
	CT01 P06	Plantroom Roof	Cooling Tower Condenser Water Pump	P06	37	Yes	Yes	Yes	Yes	Yes					
	CT02 P07	Plantroom Roof	Cooling Tower Condenser Water Pump	P07	37	Yes	Yes	Yes	Yes	Yes	Daily	Everyday	01:00	Duty/Standby	12 Hours
	CT02 P08	Plantroom Roof	Cooling Tower Condenser Water Pump	P08	37	Yes	Yes	Yes	Yes	Yes					
	CT03 P01	Plantroom Roof	Cooling Tower Condenser Water Pump	P01	37	Yes	Yes	Yes	Yes	Yes	Daily	Everyday	01:00	Duty/Standby	12 Hours
	CT03 P02	Plantroom Roof	Cooling Tower Condenser Water Pump	P02	37	Yes	Yes	Yes	Yes	Yes					
	CT04 P03	Plantroom Roof	Cooling Tower Condenser Water Pump	P03	37	Yes	Yes	Yes	Yes	Yes	Daily	Everyday	01:00	Duty/Standby	12 Hours
	CT04 P04	Plantroom Roof	Cooling Tower Condenser Water Pump	P04	37	Yes	Yes	Yes	Yes	Yes					
	CT05 P09	Plantroom Roof	Cooling Tower Condenser Water Pump	P09	30	Yes	Yes	Yes	Yes	Yes	Daily	Everyday	01:00	Duty/Standby	12 Hours
	CT05 P10	Plantroom Roof	Cooling Tower Condenser Water Pump	P10	30	Yes	Yes	Yes	Yes	Yes					
	CT06 P11	Plantroom Roof	Cooling Tower Condenser Water Pump	P11	30	Yes	Yes	Yes	Yes	Yes	Daily	Everyday	01:00	Duty/Standby	12 Hours
	CT06 P12	Plantroom Roof	Cooling Tower Condenser Water Pump	P12	30	Yes	Yes	Yes	Yes	Yes					
	AHU10 SF	Plantroom Roof	AHU Supply Fan	AHU10	22	Yes	Yes	Yes	Yes	Yes	06:00 - 19:00 Operations Monday to Friday (optimisation can mean asset starts 3 hours beforehand)				
	AHU10 EF	Plantroom Roof	AHU Extract Fan	AHU10	18.5	Yes	Yes	Yes	Yes	Yes					
	AHU09 SF	Plantroom Roof	AHU Supply Fan	AHU9	22	Yes	Yes	Yes	Yes	Yes					
	AHU09 EF	Plantroom Roof	AHU Extract Fan	AHU9	18.5	Yes	Yes	Yes	Yes	Yes					
	AHU18 SF	Plantroom Roof	AHU Supply Fan	AHU18	18.5	Yes	Yes	Yes	Yes	Yes					
	AHU18 EF	Plantroom Roof	AHU Extract Fan	AHU18	15	Yes	Yes	Yes	Yes	Yes					
	AHU17 SF	Plantroom Roof	AHU Supply Fan	AHU17	22	Yes	Yes	Yes	Yes	Yes					
	AHU17 EF	Plantroom Roof	AHU Extract Fan	AHU17	15	Yes	Yes	Yes	Yes	Yes					

11.2 APPENDIX B: PPM ACTIONS UNDERTAKEN

(Acquired from the CAFM System)

11.2.1 MONTHLY SERVICE ACTIONS

No specific monthly maintenance detailed, only the following actions are detailed:

1. Carry out visual checks
2. Check operation
3. Check for leaks

11.2.2 THREE MONTHLY SERVICE ACTIONS

1. Casings. Inspect and clean as required.
2. Bearings and Glands. Inspect for wear, lubricate bearings and motors, repack glands as required. Report if defective
3. Bolts, pulleys, couplings, belts. Inspect and adjust as required. Replace belts if worn.
4. Pump pressures. Check and record
5. Strainers. Inspect and clean as required.
6. Ball valves, float pressure and temperature switches. Check for proper operation and calibration. Check and record all temperatures.
7. Motor electrical terminals. Inspect and tighten as required. (see also MOTORS)
8. Full load running current. Check and record
9. Pulley(s). Check and realign if necessary.
10. Isolation, regulation and non-return valves. Check operation. Tighten glands or repack if necessary.
11. Drain and tundish. Check for blockage, clean.
12. Anti-vibration mounts. Check and clean. Generally report any defects to client.

11.2.3 ANNUAL SERVICE ACTIONS

At each stage, record all observations and actions taken.

GENERAL
1. Check unit for any undue noise or vibration.
2. Check local pipework and connections for leaks and corrosion.
3. Check externally mechanical seals.
4. Check flexible couplings for leaks and condition.
5. Check pump mounts are secure.
6. Check condition and operation of anti-vibration mounts and acoustic pads.
7. Check and clean all strainers.
8. Survey unit and report any refurbishment that is required.

OPERATION:
9. Check operation of pump.
10. Check that the gauge indications are correct when the pump is running.
11. Check pump output and record.
12. Check operation of non-return valves.

VALVES:
13. Check valves for full and free environment.
14. Examine suction & discharge valve gland packing.
15. Adjust or replace as required. Adjusted / Replaced?

DRIVE:
16. Check drive coupling if accessible.
17. Check condition and tension of drive belts.
18. If belts require changing, use a match set. Changed? Y / N
19. Check pulley/coupling alignment.
20. Adjust if necessary. Adjusted? Y / N
21. Check drive guard is securely fitted.
22. Lubricate pump bearings if required. Lubricated? Y / N

MOTOR:
23. Lubricate motor bearings if required. Lubricated? Y / N
24. Check motor vent louvres are clear.
25. Blow out motor windings.
26. Check operation of isolating switches/lockstops.
27. Carry out insulation resistance test and record.
28. Carry out earth continuity test and record.
29. Check motor winding resistance and record.
30. Check starting current and record.
31. Check running current and record.
32. Check terminals for tightness and signs of overheating.

11.3 APPENDIX C: ENERGY CONSUMPTION (SCHEDULED DATA)

	kW	Room	Description	No.	Hrs Run (annual)	kWHr annual	Cost	Kg CO2	Ton C02
1	18.5	Plantroom A	Primary Constant Temperature Pump	P01A	4380	81030	£6,482.40	36097.24	36.1
2	18.5	Plantroom A	Primary Constant Temperature Pump	P01B	4380	81030	£6,482.40	36097.24	36.1
3	30	Plantroom A	Secondary Constant Temperature Pump	P05A	4380	131400	£10,512.00	58536.07	58.5
4	30	Plantroom A	Secondary Constant Temperature Pump	P05B	4380	131400	£10,512.00	58536.07	58.5
5	11	Plantroom B	Primary Constant Temperature Pump	P01A	4380	48180	£3,854.40	21463.23	21.5
6	11	Plantroom B	Primary Constant Temperature Pump	P01B	4380	48180	£3,854.40	21463.23	21.5
7	18.5	Plantroom B	Secondary Constant Temperature Pump	P04A	4380	81030	£6,482.40	36097.24	36.1
8	18.5	Plantroom B	Secondary Constant Temperature Pump	P04B	4380	81030	£6,482.40	36097.24	36.1
9	55	Chilled Water Plantroom	Primary Chilled Water Pump	P01	2190	120450	£9,636.00	53658.07	53.7
10	55	Chilled Water Plantroom	Primary Chilled Water Pump	P02	2190	120450	£9,636.00	53658.07	53.7
11	55	Chilled Water Plantroom	Primary Chilled Water Pump	P03	2190	120450	£9,636.00	53658.07	53.7
12	160	Chilled Water Plantroom	Secondary Chilled Water Pump	P04	2190	350400	£28,032.00	156096.19	156.1
13	160	Chilled Water Plantroom	Secondary Chilled Water Pump	P05	2190	350400	£28,032.00	156096.19	156.1
14	18.5	Chilled Water Plantroom	Secondary Chilled Water Pump	P08	2190	40515	£3,241.20	18048.62	18.0
15	18.5	Chilled Water Plantroom	Secondary Chilled Water Pump	P09	2190	40515	£3,241.20	18048.62	18.0
16	37	Chilled Water Plantroom	Secondary Chilled Water Pump	P10	2190	81030	£6,482.40	36097.24	36.1
17	37	Chilled Water Plantroom	Secondary Chilled Water Pump	P11	2190	81030	£6,482.40	36097.24	36.1
18	132	Chilled Water Plantroom	Primary Condenser Water Pump	P20	2190	289080	£23,126.40	128779.36	128.8
19	132	Chilled Water Plantroom	Primary Condenser Water Pump	P21	2190	289080	£23,126.40	128779.36	128.8
20	132	Chilled Water Plantroom	Primary Condenser Water Pump	P22	2190	289080	£23,126.40	128779.36	128.8
21	55	Chilled Water Plantroom	Primary Chilled Water Pump	P18	4380	240900	£19,272.00	107316.13	107.3

	kW	Room	Description	No.	Hrs Run (annual)	kWHr annual	Cost	Kg CO2	Ton C02
22	55	Chilled Water Plantroom	Primary Chilled Water Pump	P19	4380	240900	£19,272.00	107316.13	107.3
23	45	Chilled Water Plantroom	Primary Condenser Water Pump	P23	4380	197100	£15,768.00	87804.11	87.8
24	45	Chilled Water Plantroom	Primary Condenser Water Pump	P24	4380	197100	£15,768.00	87804.11	87.8
25	37	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P05	2190	81030	£6,482.40	36097.24	36.1
26	37	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P06	2190	81030	£6,482.40	36097.24	36.1
27	37	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P07	2190	81030	£6,482.40	36097.24	36.1
28	37	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P08	2190	81030	£6,482.40	36097.24	36.1
29	37	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P01	2190	81030	£6,482.40	36097.24	36.1
30	37	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P02	2190	81030	£6,482.40	36097.24	36.1
31	37	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P03	2190	81030	£6,482.40	36097.24	36.1
32	37	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P04	2190	81030	£6,482.40	36097.24	36.1
33	30	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P09	2190	65700	£5,256.00	29268.04	29.3
34	30	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P10	2190	65700	£5,256.00	29268.04	29.3
35	30	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P11	2190	65700	£5,256.00	29268.04	29.3
36	30	9th Floor Roof Chilled Water	Cooling Tower Condenser Water Pump	P12	2190	65700	£5,256.00	29268.04	29.3
37	22	Roof Areas 9&10	General Office Air Handling Unit	AHU10	3120	68640	£5,491.20	30577.75	30.6
38	18.5	Roof Areas 9&10	General Office Air Handling Unit	AHU10	3120	57720	£4,617.60	25713.11	25.7
39	22	Roof Areas 9&10	General Office Air Handling Unit	AHU9	3120	68640	£5,491.20	30577.75	30.6
40	18.5	Roof Areas 9&10	General Office Air Handling Unit	AHU9	3120	57720	£4,617.60	25713.11	25.7
41	18.5	Roof Areas 9&10	General Office Air Handling Unit	AHU18	3120	57720	£4,617.60	25713.11	25.7
42	15	Roof Areas 9&10	General Office Air Handling Unit	AHU18	3120	46800	£3,744.00	20848.46	20.8
43	22	Roof Areas 9&10	General Office Air Handling Unit	AHU17	3120	68640	£5,491.20	30577.75	30.6
44	15	Roof Areas 9&10	General Office Air Handling Unit	AHU17	3120	46800	£3,744.00	20848.46	20.8

11.4 APPENDIX D: RAW DATA EXTRACTION

Example of Raw data output from BMS

Point_220:	MB.B203.B02.EB1.PR.A.P04A-G120:FREQ OUTPUT
Point_221:	MB.B203.B02.EB1.PR.A.P04A-G120:SPEED
Point_222:	MB.B203.B02.EB1.PR.A.P04A-G120:STOP RUN
Point_223:	MB.B203.B02.EB1.PR.A.P04A-G120:TORQUE
Point_224:	MB.B203.B02.EB1.PR.A.P04A-G120:TOTAL KWH
Point_225:	MB.B202.B02.ES4.PR.B.P2A-G120:ACTUAL PWR
Point_226:	MB.B202.B02.ES4.PR.B.P2A-G120:CURRENT
Point_227:	MB.B202.B02.ES4.PR.B.P2A-G120:FREQ OUTPUT
Point_228:	MB.B202.B02.ES4.PR.B.P2A-G120:SPEED
Point_229:	MB.B202.B02.ES4.PR.B.P2A-G120:STOP RUN
Point_230:	MB.B202.B02.ES4.PR.B.P2A-G120:TORQUE
Point_231:	MB.B202.B02.ES4.PR.B.P2A-G120:TOTAL KWH
Point_232:	B203.P05B-SED2:ACTUAL PWR
Point_233:	B203.P05B-SED2:CURRENT
Point_234:	B203.P05B-SED2:FREQ OUTPUT
Point_235:	B203.P05B-SED2:SPEED
Point_236:	B203.P05B-SED2:STOP RUN
Point_237:	B203.P05B-SED2:TORQUE
Point_238:	B203.P05B-SED2:TOTAL KWH
Point_239:	B208.P11-SED2:ACTUAL PWR
Point_240:	B208.P11-SED2:CURRENT
Point_241:	B208.P11-SED2:FREQ OUTPUT
Point_242:	B208.P11-SED2:SPEED
Point_243:	B208.P11-SED2:STOP RUN
Point_244:	B208.P11-SED2:TORQUE
Point_245:	B208.P11-SED2:TOTAL KWH
Time Interval:	5 Minutes
Date Range:	21/03/2016 00:00:00 - 28/03/2016 23:59:59
Report Timings	All Hours

<>Date	Time	Point_1	Point_2	Point_3	Point_4	Point_5	Point_6	Point_7	Point_8	Point_9	Point_10	Point_11	Point_12	Point_13	Point_14	Point_15	Point_16
21/03/2016	00:00:00	26613	0	STOP	0	0	0.05	0	13082	29.2	RUN	1200	40	10.2	3.57	0	0
21/03/2016	00:05:00	26613	0	STOP	0	0	0.05	0	13082	29.2	RUN	1200	40	10.2	3.57	0	0
21/03/2016	00:10:00	26613	0	STOP	0	0	0.05	0	13082	29.2	RUN	1200	40	10.2	3.57	0	0
21/03/2016	00:15:00	26613	0	STOP	0	0	0.05	0	13082	28.4	RUN	1200	40	10.25	3.57	0	0
21/03/2016	00:20:00	26613	0	STOP	0	0	0.05	0	13082	28.4	RUN	1200	40	10.25	3.57	0	0
21/03/2016	00:25:00	26613	0	STOP	0	0	0.05	0	13082	28.4	RUN	1200	40	10.25	3.57	0	0
21/03/2016	00:30:00	26613	0	STOP	0	0	0.05	0	13082	28.6	RUN	1200	40	10.25	3.52	0	0
21/03/2016	00:35:00	26613	0	STOP	0	0	0.05	0	13082	28.6	RUN	1200	40	10.25	3.52	0	0
21/03/2016	00:40:00	26613	0	STOP	0	0	0.05	0	13082	28.6	RUN	1200	40	10.25	3.52	0	0
21/03/2016	00:45:00	26613	0	STOP	0	0	0.05	0	13082	28.4	RUN	1200	40	10.2	3.56	0	0
21/03/2016	00:50:00	26613	0	STOP	0	0	0.05	0	13082	28.4	RUN	1200	40	10.2	3.56	0	0
21/03/2016	00:55:00	26613	0	STOP	0	0	0.05	0	13082	28.4	RUN	1200	40	10.2	3.56	0	0
21/03/2016	01:00:00	26613	0	STOP	0	0	0.05	0	13084	28.4	RUN	1200	40	10.2	3.53	0	0

11.5 APPENDIX E: TEMPERATURE AND HUMIDITY RESULTS

	OUTSIDE				**PR A**				**PR B**				**PR Chiller**				**CT 01 & 02**				**CT 03 & 04**			
	Mean		**StdDev**		**Mean**		**StdDev**		**Mean**		**StdDev**		**Mean**		**StdDev**		**Mean**		**StdDev**		**Mean**		**StdDev**	
MONTH	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*
JAN	75.47	8.05	10.08	2.89	13.13	49.65	4.18	3.61	20.56	30.44	3.81	0.81	27.67	25.21	5.62	0.60	71.26	8.81	10.27	2.44	67.95	10.14	9.88	2.55
FEB	75.69	7.17	10.67	2.73	12.48	48.73	3.68	3.68	19.89	30.15	2.63	1.36	27.12	24.96	4.40	0.48	69.53	8.62	10.00	2.09	66.27	9.60	9.55	2.08
MAR	67.87	9.52	13.32	2.47	13.33	48.17	3.78	4.15	20.20	30.01	2.92	0.56	27.44	25.21	3.68	0.49	62.41	10.84	12.24	2.01	60.52	11.64	10.85	2.19
APR	62.11	13.00	13.68	3.43	20.34	43.58	5.49	3.15	17.00	29.80	0.04	0.04	27.65	27.11	3.78	1.02	58.18	14.03	13.20	3.05	57.61	14.48	11.71	3.13
MAY	63.32	14.78	13.96	3.02	19.66	45.78	4.24	3.33	17.00	29.80	0.00	0.00	30.64	27.15	3.74	1.06	59.58	16.15	13.40	2.59	58.27	16.84	12.51	4.25
JUN	61.23	18.00	13.50	3.81	21.38	46.22	4.43	3.17	17.00	29.80	0.00	0.00	34.49	27.69	4.70	0.65	57.30	19.96	12.51	3.26	57.07	20.62	11.03	2.99
JUL	61.98	20.39	15.72	3.64	23.81	46.39	3.97	3.59	27.90	30.73	6.45	0.66	37.46	28.43	4.79	0.74	57.78	22.16	13.61	3.00	58.36	22.85	13.65	3.08
AUG	70.33	19.40	16.03	2.84	23.43	46.98	3.29	3.28	32.95	30.97	2.99	0.42	40.99	27.99	4.13	0.46	66.17	21.21	12.85	2.11	66.01	22.00	13.19	2.04
SEP	72.69	15.67	13.94	2.38	22.45	45.82	3.40	3.18	31.84	29.10	2.65	0.91	38.56	26.75	3.04	0.54	67.31	18.06	11.38	1.89	66.84	18.56	10.81	1.87
OCT	79.47	13.82	12.03	2.39	26.71	41.20	5.01	4.61	31.92	28.66	3.77	0.56	38.02	26.39	4.42	0.59	71.51	16.74	10.86	2.14	70.85	17.17	10.16	1.97
NOV	86.89	12.66	7.67	2.70	21.31	46.61	5.80	4.04	31.05	29.41	3.93	0.83	39.70	25.56	4.22	0.90	82.46	14.01	5.80	2.62	79.05	15.01	6.16	2.53
DEC	77.01	8.58	9.76	3.07	14.28	49.21	4.80	4.19	22.13	30.47	4.29	0.55	28.50	24.92	3.42	0.62	72.36	9.58	9.04	2.64	68.97	10.87	8.12	2.74

	CT 05				CT 06				AHU 09				AHU 10				AHU 17				AHU 18			
	Mean		StdDev		Mean		StdDev		Mean		StdDev		Mean		StdDev		Mean		StdDev		Mean		StdDev	
MONTH	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*	*HUM*	*TEMP*
JAN	36.94	18.92	5.35	1.56	38.34	20.67	6.39	0.91	55.65	15.50	9.42	1.45	44.17	17.00	10.71	4.21	45.22	18.15	5.24	1.13	35.93	21.18	6.83	0.52
FEB	35.29	18.67	4.24	1.64	32.23	21.51	3.88	1.44	53.20	15.31	7.70	1.29	44.43	15.93	11.35	4.44	42.77	18.38	4.20	1.17	30.82	21.72	4.26	1.03
MAR	33.77	20.20	4.37	1.27	31.93	22.20	4.21	0.58	48.80	17.54	7.74	0.97	43.11	16.90	12.19	4.55	42.62	19.21	4.80	1.04	29.95	22.65	4.44	0.67
APR	33.65	22.22	4.53	1.95	31.58	24.86	4.67	1.16	46.04	19.93	8.18	1.77	45.01	17.84	12.32	4.88	39.65	21.71	5.50	1.51	29.60	25.25	4.34	1.03
MAY	36.01	22.88	5.20	2.26	32.13	26.09	4.46	0.99	47.22	21.61	7.03	1.55	42.99	20.67	9.90	4.00	40.94	22.26	4.78	1.38	31.49	25.74	4.68	1.10
JUN	37.33	25.11	5.85	1.86	37.91	26.70	5.99	1.56	48.72	23.84	8.75	1.56	47.24	21.64	9.73	3.69	44.58	23.87	5.98	1.54	36.49	25.95	5.98	1.19
JUL	41.37	25.48	7.99	2.94	38.88	28.50	5.84	1.64	51.07	25.39	9.78	1.88	48.45	23.93	10.79	3.11	46.60	25.04	7.29	1.73	38.24	27.39	6.27	1.68
AUG	41.92	26.10	6.00	1.69	43.11	27.88	5.34	0.99	56.83	24.54	9.66	1.20	53.06	23.62	11.30	2.55	53.94	23.56	10.79	2.12	42.34	26.84	5.23	1.01
SEP	41.47	23.53	4.32	1.60	42.95	25.27	4.09	0.90	55.64	21.86	7.04	1.01	53.25	20.27	10.66	2.84	54.65	20.33	6.52	1.29	41.24	24.71	4.25	0.98
OCT	47.04	21.06	7.93	2.25	41.75	25.03	5.24	0.95	59.29	20.50	8.29	1.32	54.76	19.53	11.76	3.95	54.88	20.32	6.55	1.87	39.93	24.55	5.39	0.95
NOV	46.82	21.30	6.10	1.84	46.58	24.12	4.11	1.25	68.81	18.76	7.33	1.87	56.18	19.79	11.44	4.47	58.47	19.37	5.54	2.27	44.49	24.16	4.11	0.81
DEC	38.02	19.46	5.57	1.59	39.77	21.40	5.30	1.24	59.06	16.36	9.49	1.68	43.43	18.44	12.25	4.08	46.51	18.72	5.33	1.16	37.34	21.82	5.59	0.89

11.6 APPENDIX F: OPERATIONS AND ENERGY RESULTS – BASEMENT

Ops and Energy Results		JAN						FEB					
	kW	*N*	*Cum. Current (A)*	*Mean. Current (A)*	*Hrs*	*kWh*	*£*	*N*	*Cum. Current (A)*	*Mean. Current (A)*	*Hrs*	*kWh*	*£*
PLA_P01A_CURRENT	18.5	3345	110470	33.0	278.8	5156.9	412.55	3090	102007	33.0	257.5	4763.8	381.1
PLA_P01B_CURRENT	18.5	5508	124710	22.6	459.0	8491.5	679.32	4953	112097	22.6	412.8	7635.9	610.9
PLA_P05A_CURRENT	30	5142	123870	24.1	428.5	12855.0	1,028.40	4781	114584	24.0	398.4	11952.5	956.2
PLA_P05B_CURRENT	30	3708	94209	25.4	309.0	9270.0	741.60	3259	82454	25.3	271.6	8147.5	651.8
PLB_P01A_CURRENT	11	4192	49981	11.9	349.3	3842.7	307.41	3735	44469	11.9	311.3	3423.8	273.9
PLB_P01B_CURRENT	11	4550	46096	10.1	379.2	4170.8	333.67	3843	38948	10.1	320.3	3522.8	281.8
PLB_P04A_CURRENT	18.5	8732	190052	21.8	727.7	13461.8	1,076.95	3831	84305	22.0	319.3	5906.1	472.5
PLB_P04B_CURRENT	18.5	0	0	0.0	0.0	0.0	0.00	3562	115432	32.4	296.8	5491.4	439.3
CHW_P01_CURRENT	55	1368	78234	57.2	114.0	6270.0	501.60	2385	132392	55.5	198.8	10931.3	874.5
CHW_P02_CURRENT	55	2193	131277	59.9	182.8	10051.3	804.10	2055	109694	53.4	171.3	9418.8	753.5
CHW_P03_CURRENT	55	1989	79194	39.8	165.8	9116.3	729.30	1194	47182	39.5	99.5	5472.5	437.8
CHW_P08_CURRENT	18.5	1449	23271	16.1	120.8	2233.9	178.71	1386	22495	16.2	115.5	2136.8	170.9
CHW_P09_CURRENT	18.5	1317	21885	16.6	109.8	2030.4	162.43	1422	23770	16.7	118.5	2192.3	175.4
CHW_P10_CURRENT	37	1449	49877	34.4	120.8	4467.8	357.42	1389	48902	35.2	115.8	4282.8	342.6
CHW_P11_CURRENT	37	1314	42254	32.2	109.5	4051.5	324.12	1422	48215	33.9	118.5	4384.5	350.8
CHW_P18_CURRENT	55	5301	342389	64.6	441.8	24296.3	1,943.70	4032	260328	64.6	336.0	18480.0	1478.4
CHW_P19_CURRENT	55	3615	229261	63.4	301.3	16568.8	1,325.50	4032	256641	63.7	336.0	18480.0	1478.4
CHW_P24_CURRENT	45	5808	440390	75.8	484.0	21780.0	1,742.40	4032	306325	76.0	336.0	15120.0	1209.6
CHW_P23_CURRENT	45	3126	229050	73.3	260.5	11722.5	937.80	4032	295639	73.3	336.0	15120.0	1209.6

Ops and Energy Results		MAR						APR					
	kW	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***
PLA_P01A_CURRENT	18.5	2907	96058	33.0	242.3	4481.6	358.5	1366	45192	33.1	113.8	2105.9	168.5
PLA_P01B_CURRENT	18.5	3717	84123	22.6	309.8	5730.4	458.4	6693	151053	22.6	557.8	10318.4	825.5
PLA_P05A_CURRENT	30	4002	95570	23.9	333.5	10005.0	800.4	5060	120755	23.9	421.7	12650.0	1012.0
PLA_P05B_CURRENT	30	2622	66374	25.3	218.5	6555.0	524.4	2999	75781	25.3	249.9	7497.5	599.8
PLB_P01A_CURRENT	11	3182	37854	11.9	265.2	2916.8	233.3	0	0	0	0.0	0.0	0.0
PLB_P01B_CURRENT	11	3441	34913	10.1	286.8	3154.3	252.3	0	0	0	0.0	0.0	0.0
PLB_P04A_CURRENT	18.5	3132	68581	21.9	261.0	4828.5	386.3	0	0	0	0.0	0.0	0.0
PLB_P04B_CURRENT	18.5	3442	111266	32.3	286.8	5306.4	424.5	0	0	0	0.0	0.0	0.0
CHW_P01_CURRENT	55	1428	79154	55.4	119.0	6545.0	523.6	0	0	0	0.0	0.0	0.0
CHW_P02_CURRENT	55	1722	97186	56.4	143.5	7892.5	631.4	0	0	0	0.0	0.0	0.0
CHW_P03_CURRENT	55	1134	45280	39.9	94.5	5197.5	415.8	0	0	0	0.0	0.0	0.0
CHW_P08_CURRENT	18.5	849	14517	17.1	70.8	1308.9	104.7	0	0	0	0.0	0.0	0.0
CHW_P09_CURRENT	18.5	1287	21956	17.1	107.3	1984.1	158.7	0	0	0	0.0	0.0	0.0
CHW_P10_CURRENT	37	849	30176	35.5	70.8	2617.8	209.4	0	0	0	0.0	0.0	0.0
CHW_P11_CURRENT	37	1287	45186	35.1	107.3	3968.3	317.5	0	0	0	0.0	0.0	0.0
CHW_P18_CURRENT	55	3903	254000	65.1	325.3	17888.8	1431.1	3300	214758	65.1	275.0	15125.0	1210.0
CHW_P19_CURRENT	55	2721	172829	63.5	226.8	12471.3	997.7	4764	303111	63.6	397.0	21835.0	1746.8
CHW_P24_CURRENT	45	2439	185242	76.0	203.3	9146.3	731.7	4725	359581	76.1	393.8	17718.8	1417.5
CHW_P23_CURRENT	45	4185	306449	73.2	348.8	15693.8	1255.5	3342	244395	73.1	278.5	12532.5	1002.6

Ops and Energy Results		MAY						JUN					
	kW	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***
PLA_P01A_CURRENT	18.5	2655	87715	33.0	221.3	4093.1	327.5	2587	85518	33.1	215.6	3988.3	319.1
PLA_P01B_CURRENT	18.5	6273	143498	22.9	522.8	9670.9	773.7	6051	141063	23.3	504.3	9328.6	746.3
PLA_P05A_CURRENT	30	4663	107944	23.1	388.6	11657.5	932.6	4623	106756	23.1	385.3	11557.5	924.6
PLA_P05B_CURRENT	30	4065	99337	24.4	338.8	10162.5	813.0	4014	98408	24.5	334.5	10035.0	802.8
PLB_P01A_CURRENT	11	412	4894	11.9	34.3	377.7	30.2	4317	51296	11.9	359.8	3957.3	316.6
PLB_P01B_CURRENT	11	561	5663	10.1	46.8	514.3	41.1	4059	41011	10.1	338.3	3720.8	297.7
PLB_P04A_CURRENT	18.5	190	4176	22.0	15.8	292.9	23.4	3156	69160	21.9	263.0	4865.5	389.2
PLB_P04B_CURRENT	18.5	459	14907	32.5	38.3	707.6	56.6	3213	104005	32.4	267.8	4953.4	396.3
CHW_P01_CURRENT	55	0	0	0.0	0.0	0.0	0.0	2421	128913	53.2	201.8	11096.3	887.7
CHW_P02_CURRENT	55	210	13497	64.3	17.5	962.5	77.0	2934	161307	55.0	244.5	13447.5	1075.8
CHW_P03_CURRENT	55	209	8318	39.8	17.4	957.9	76.6	1365	52246	38.3	113.8	6256.3	500.5
CHW_P08_CURRENT	18.5	188	3270	17.4	15.7	289.8	23.2	1386	28917	20.9	115.5	2136.8	170.9
CHW_P09_CURRENT	18.5	0	0	0.0	0.0	0.0	0.0	1797	36505	20.3	149.8	2770.4	221.6
CHW_P10_CURRENT	37	187	6754	36.1	15.6	576.6	46.1	1182	45209	38.2	98.5	3644.5	291.6
CHW_P11_CURRENT	37	0	0	0.0	0.0	0.0	0.0	2007	75324	37.5	167.3	6188.3	495.1
CHW_P18_CURRENT	55	7293	476502	65.3	607.8	33426.3	2674.1	5307	344562	64.9	442.3	24323.8	1945.9
CHW_P19_CURRENT	55	1635	104413	63.9	136.3	7493.8	599.5	3333	291725	87.5	277.8	15276.3	1222.1
CHW_P24_CURRENT	45	4896	371882	76.0	408.0	18360.0	1468.8	4167	315549	75.7	347.3	15626.3	1250.1
CHW_P23_CURRENT	45	3765	275583	73.2	313.8	14118.8	1129.5	4473	326703	73.0	372.8	16773.8	1341.9

Ops and Energy Results		JUL						AUG					
	kW	*N*	*Cum. Current (A)*	*Mean. Current (A)*	*Hrs*	*kWh*	*£*	*N*	*Cum. Current (A)*	*Mean. Current (A)*	*Hrs*	*kWh*	*£*
PLA_P01A_CURRENT	18.5	2010	66367	33.0	167.5	3098.8	247.9	0	0	0	0	0	0
PLA_P01B_CURRENT	18.5	4902	114545	23.4	408.5	7557.3	604.6	576	13488	23.4	28.8	532.8	42.624
PLA_P05A_CURRENT	30	3651	83348	22.8	304.3	9127.5	730.2	561	12789	22.8	28.05	841.5	67.32
PLA_P05B_CURRENT	30	3261	80170	24.6	271.8	8152.5	652.2	15	371	24.7	0.75	22.5	1.8
PLB_P01A_CURRENT	11	3539	42038	11.9	294.9	3244.1	259.5	288	3422	11.9	14.4	158.4	12.672
PLB_P01B_CURRENT	11	3364	33976	10.1	280.3	3083.7	246.7	288	2912	10.1	14.4	158.4	12.672
PLB_P04A_CURRENT	18.5	2647	57945	21.9	220.6	4080.8	326.5	36	791	22.0	1.8	33.3	2.664
PLB_P04B_CURRENT	18.5	2885	93337	32.4	240.4	4447.7	355.8	171	5539	32.4	8.55	158.175	12.654
CHW_P01_CURRENT	55	600	32579	54.3	50.0	2750.0	220.0	0	0	0	0	0	0
CHW_P02_CURRENT	55	2871	179662	62.6	239.3	13158.8	1052.7	0	0	0	0	0	0
CHW_P03_CURRENT	55	2559	99443	38.9	213.3	11728.8	938.3	0	0	0	0	0	0
CHW_P08_CURRENT	18.5	1407	28431	20.2	117.3	2169.1	173.5	0	0	0	0	0	0
CHW_P09_CURRENT	18.5	1587	32686	20.6	132.3	2446.6	195.7	0	0	0	0	0	0
CHW_P10_CURRENT	37	1536	58243	37.9	128.0	4736.0	378.9	0	0	0	0	0	0
CHW_P11_CURRENT	37	1060	40813	38.5	88.3	3268.3	261.5	0	0	0	0	0	0
CHW_P18_CURRENT	55	2721	170145	62.5	226.8	12471.3	997.7	576	36283	63.0	28.8	1584	126.72
CHW_P19_CURRENT	55	4173	356070	85.3	347.8	19126.3	1530.1	0	0	0	0	0	0
CHW_P24_CURRENT	45	2151	163244	75.9	179.3	8066.3	645.3	0	0	0	0	0	0
CHW_P23_CURRENT	45	4776	349216	73.1	398.0	17910.0	1432.8	576	41982	72.9	28.8	1296	103.68

Ops and Energy Results		SEP						OCT					
	kW	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***
PLA_P01A_CURRENT	18.5							0	0	0	0	0	0
PLA_P01B_CURRENT	18.5							0	0	0.0	0	0	0
PLA_P05A_CURRENT	30							0	0	0.0	0	0	0
PLA_P05B_CURRENT	30							0	0	0.0	0	0	0
PLB_P01A_CURRENT	11							0	0	0.0	0	0	0
PLB_P01B_CURRENT	11							574	5836	10.2	47.83333333	526.1666667	42.09333333
PLB_P04A_CURRENT	18.5							586	12842	21.9	48.83333333	903.4166667	72.27333333
PLB_P04B_CURRENT	18.5										0	0	0
CHW_P01_CURRENT	55							288	16406	57.0	24	1320	105.6
CHW_P02_CURRENT	55							189	10176	53.8	15.75	866.25	69.3
CHW_P03_CURRENT	55							189	7365	39.0	15.75	866.25	69.3
CHW_P08_CURRENT	18.5							333	5647	17.0	27.75	513.375	41.07
CHW_P09_CURRENT	18.5							0	0	0.0	0	0	0
CHW_P10_CURRENT	37							213	7276	34.2	17.75	656.75	52.54
CHW_P11_CURRENT	37							120	4129	34.4	10	370	29.6
CHW_P18_CURRENT	55							0	0	0.0	0	0	0
CHW_P19_CURRENT	55							689	44129	64.0	57.41666667	3157.916667	252.6333333
CHW_P24_CURRENT	45							689	52315	75.9	57.41666667	2583.75	206.7
CHW_P23_CURRENT	45							0	0	0.0	0	0	0

Ops and Energy Results		NOV						DEC					
	kW	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***
PLA_P01A_CURRENT	18.5	1824	60284	33.1	152.0	2812.0	225.0	2799	92494	33.0	233.3	4315.1	345.2
PLA_P01B_CURRENT	18.5	3350	76046	22.7	279.2	5164.6	413.2	6108	138373	22.7	509.0	9416.5	753.3
PLA_P05A_CURRENT	30	0	0	0.0	0.0	0.0	0.0	3591	85928	23.9	299.3	8977.5	718.2
PLA_P05B_CURRENT	30	2466	62022	25.2	205.5	6165.0	493.2	3495	88194	25.2	291.3	8737.5	699.0
PLB_P01A_CURRENT	11	0	0	0.0	0.0	0.0	0.0	3137	37402	11.9	261.4	2875.6	230.0
PLB_P01B_CURRENT	11	4289	43474	10.1	357.4	3931.6	314.5	4483	45451	10.1	373.6	4109.4	328.8
PLB_P04A_CURRENT	18.5	7467	163640	21.9	622.3	11511.6	920.9	8627	187576	21.7	718.9	13300.0	1064.0
PLB_P04B_CURRENT	18.5	0	0	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.0	0.0
CHW_P01_CURRENT	55	1456	83480	57.3	121.3	6673.3	533.9	1385	79181	57.2	115.4	6347.9	507.8
CHW_P02_CURRENT	55	1459	84476	57.9	121.6	6687.1	535.0	1827	108656	59.5	152.3	8373.8	669.9
CHW_P03_CURRENT	55	1466	58581	40.0	122.2	6719.2	537.5	1859	74620	40.1	154.9	8520.4	681.6
CHW_P08_CURRENT	18.5	758	12388	16.3	63.2	1168.6	93.5	1410	23107	16.4	117.5	2173.8	173.9
CHW_P09_CURRENT	18.5	1421	24593	17.3	118.4	2190.7	175.3	1113	17735	15.9	92.8	1715.9	137.3
CHW_P10_CURRENT	37	1385	46927	33.9	115.4	4270.4	341.6	789	26634	33.8	65.8	2432.8	194.6
CHW_P11_CURRENT	37	749	25281	33.8	62.4	2309.4	184.8	1746	58242	33.4	145.5	5383.5	430.7
CHW_P18_CURRENT	55	4251	273198	64.3	354.3	19483.8	1558.7	3887	248527	63.9	323.9	17815.4	1425.2
CHW_P19_CURRENT	55	4401	281199	63.9	366.8	20171.3	1613.7	4614	290254	62.9	384.5	21147.5	1691.8
CHW_P24_CURRENT	45	4212	320298	76.0	351.0	15795.0	1263.6	5904	449563	76.1	492.0	22140.0	1771.2
CHW_P23_CURRENT	45	4443	326397	73.5	370.3	16661.3	1332.9	2469	183740	74.4	205.8	9258.8	740.7

11.7 APPENDIX G: OPERATIONS AND ENERGY RESULTS – ROOF

Ops and Energy Results		JAN						FEB					
ASSET	***kW***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***
AHU09 EF	18.5	3396	102294	30.12	283.0	5235.5	418.84	3267	98851	30.26	272.3	5036.6	402.93
AHU09 SF	22	3396	168490	49.61	283.0	6226	498.08	3267	162504	49.74	272.3	5989.5	479.16
AHU10 EF	18.5	3327	98690	29.66	277.3	5129.125	410.33	3357	99974	29.78	279.8	5175.4	414.03
AHU10 SF	22	3396	109409	32.22	283.0	6226	498.08	3537	114682	32.42	294.8	6484.5	518.76
AHU17 EF	15	3423	83845	24.49	285.3	4278.75	342.30	3222	79288	24.61	268.5	4027.5	322.20
AHU17 SF	22	3444	118077	34.28	287.0	6314	505.12	3189	90441	28.36	265.8	5846.5	467.72
AHU18 EF	15	3459	132280	38.24	288.3	4323.75	345.90	3282	126024	38.40	273.5	4102.5	328.20
AHU18 SF	18.5	3459	105160	30.40	288.3	5332.625	426.61	3255	99880	30.69	271.3	5018.1	401.45
CT01 P05	37	1062	35676	33.59	88.5	3274.5	261.96	1326	43556	32.85	110.5	4088.5	327.08
CT01 P06	37	522	20201	38.70	43.5	1609.5	128.76	255	8319	32.62	21.3	786.3	62.90
CT02 P07	37	108	4192	38.82	9.0	333	26.64	357	11047	30.94	29.8	1100.8	88.06
CT02 P08	37	147	5105	34.73	12.3	453.25	36.26	501	15993	31.92	41.8	1544.8	123.58
CT03 P01	37	384	11457	29.83	32.0	1184	94.72	1175	34996	29.78	97.9	3622.9	289.83
CT03 P02	37	1263	37300	29.53	105.3	3894.25	311.54	453	13046	28.80	37.8	1396.8	111.74
CT04 P03	37	1464	43702	29.85	122.0	4514	361.12	1664	49371	29.67	138.7	5130.7	410.45
CT04 P04	37	1377	40660	29.53	114.8	4245.75	339.66	1302	35112	26.97	108.5	4014.5	321.16
CT05 P09	30	2109	68338	32.40	175.8	5272.5	421.80	2016	65141	32.31	168.0	5040.0	403.20
CT05 P10	30	2304	76918	33.38	192.0	5760	460.80	2016	67346	33.41	168.0	5040.0	403.20
CT06 P11	30	2346	60421	25.75	195.5	5865	469.20	2016	53279	26.43	168.0	5040.0	403.20
CT06 P12	30	2163	54515	25.20	180.3	5407.5	432.60	2016	50675	25.14	168.0	5040.0	403.20

Ops and Energy Results		MAR						APR					
ASSET	***kW***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***
AHU09 EF	18.5	3285	99436	30.27	273.8	5064.4	405.15	4982	149913	30.09	415.2	7680.6	614.45
AHU09 SF	22	3354	167358	49.90	279.5	6149.0	491.92	4982	246389	49.46	415.2	9133.7	730.69
AHU10 EF	18.5	3808	113493	29.80	317.3	5870.7	469.65	5247	155828	29.70	437.3	8089.1	647.13
AHU10 SF	22	3952	128502	32.52	329.3	7245.3	579.63	5559	179704	32.33	463.3	10191.5	815.32
AHU17 EF	15	3307	81844	24.75	275.6	4133.8	330.70	3663	90542	24.72	305.3	4578.8	366.30
AHU17 SF	22	4750	206739	43.52	395.8	8708.3	696.67	3752	163197	43.50	312.7	6878.7	550.29
AHU18 EF	15	3406	130665	38.36	283.8	4257.5	340.60	3752	143549	38.26	312.7	4690.0	375.20
AHU18 SF	18.5	3406	104694	30.74	283.8	5250.9	420.07	3755	115301	30.71	312.9	5789.0	463.12
CT01 P05	37	1252	42465	33.92	104.3	3860.3	308.83	45	1496	33.25	3.8	138.8	11.10
CT01 P06	37	357	10673	29.90	29.8	1100.8	88.06	3	124	41.20	0.3	9.3	0.74
CT02 P07	37	304	9471	31.16	25.3	937.3	74.99	42	1215	28.92	3.5	129.5	10.36
CT02 P08	37	351	10406	29.65	29.3	1082.3	86.58	3	127	42.40	0.3	9.3	0.74
CT03 P01	37	1698	48028	28.28	141.5	5235.5	418.84	288	7813	27.13	24.0	888.0	71.04
CT03 P02	37	361	10325	28.60	30.1	1113.1	89.05	184	5029	27.33	15.3	567.3	45.39
CT04 P03	37	1707	51084	29.93	142.3	5263.3	421.06	288	7823	27.16	24.0	888.0	71.04
CT04 P04	37	1307	37852	28.96	108.9	4029.9	322.39	184	4850	26.36	15.3	567.3	45.39
CT05 P09	30	2157	69601	32.27	179.8	5392.5	431.40	2253	72905	32.36	187.8	5632.5	450.60
CT05 P10	30	2250	75057	33.36	187.5	5625.0	450.00	2082	69444	33.35	173.5	5205.0	416.40
CT06 P11	30	2205	68447	31.04	183.8	5512.5	441.00	2187	70057	32.03	182.3	5467.5	437.40
CT06 P12	30	2304	72097	31.29	192.0	5760.0	460.80	2151	69276	32.21	179.3	5377.5	430.20

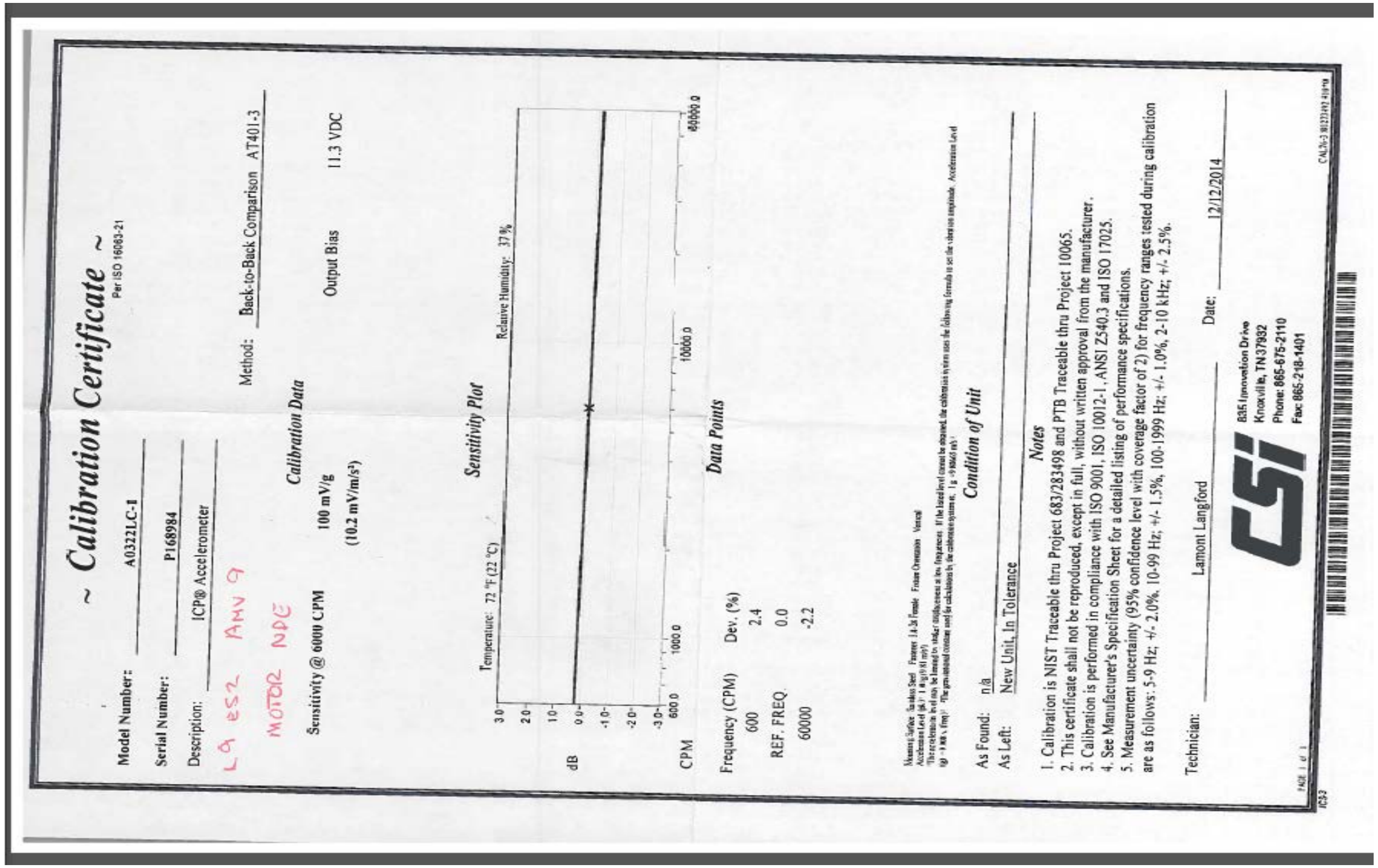
Ops and Energy Results		MAY						JUN					
ASSET	***kW***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***
AHU09 EF	18.5	3711	110863	29.87	309.3	5721.1	457.69	4582	136954	29.89	381.8	7063.9	565.11
AHU09 SF	22	3810	188642	49.51	317.5	6985.0	558.80	4597	228544	49.72	383.1	8427.8	674.23
AHU10 EF	18.5	3823	112755	29.49	318.6	5893.8	471.50	4779	141661	29.64	398.3	7367.6	589.41
AHU10 SF	22	3955	126979	32.11	329.6	7250.8	580.07	4779	154517	32.33	398.3	8761.5	700.92
AHU17 EF	15	3805	94188	24.75	317.1	4756.3	380.50	4592	114166	24.86	382.7	5740.0	459.20
AHU17 SF	22	3856	166163	43.09	321.3	7069.3	565.55	4648	201007	43.25	387.3	8521.3	681.71
AHU18 EF	15	3705	141823	38.28	308.8	4631.3	370.50	4600	177123	38.51	383.3	5750.0	460.00
AHU18 SF	18.5	3855	118184	30.66	321.3	5943.1	475.45	4651	143156	30.78	387.6	7170.3	573.62
CT01 P05	37	144	4860	33.75	12.0	444.0	35.52	1557	63125	40.54	129.8	4800.8	384.06
CT01 P06	37	112	4436	39.61	9.3	345.3	27.63	1482	67668	45.66	123.5	4569.5	365.56
CT02 P07	37	0	0	0	0.0	0.0	0.00	1035	48512	46.87	86.3	3191.3	255.30
CT02 P08	37	0	0	0	0.0	0.0	0.00	0	0	0	0.0	0.0	0.00
CT03 P01	37	201	10039	49.94	16.8	619.8	49.58	1837	86274	46.96	153.1	5664.1	453.13
CT03 P02	37	0	0	0	0.0	0.0	0.00	839	38863	46.32	69.9	2586.9	206.95
CT04 P03	37	21	815	38.79	1.8	64.8	5.18	999	41762	41.80	83.3	3080.3	246.42
CT04 P04	37	0	0	0	0.0	0.0	0.00	653	30399	46.55	54.4	2013.4	161.07
CT05 P09	30	1152	37615	32.65	96.0	2880.0	230.40	0	0	0	0.0	0.0	0.00
CT05 P10	30	1383	45820	33.13	115.3	3457.5	276.60	0	0	0	0.0	0.0	0.00
CT06 P11	30	2070	67406	32.56	172.5	5175.0	414.00	0	0	0	0.0	0.0	0.00
CT06 P12	30	2433	78216	32.15	202.8	6082.5	486.60	0	0	0	0.0	0.0	0.00

Ops and Energy Results		JUL						AUG					
ASSET	***kW***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***
AHU09 EF	18.5	3836	114084	29.74	319.7	5913.8	473.11	3816	116132	30.43	318.0	5883.0	470.64
AHU09 SF	22	4007	197660	49.33	333.9	7346.2	587.69	4884	240659	49.28	407.0	8954.0	716.32
AHU10 EF	18.5	3945	116324	29.49	328.8	6081.9	486.55	3379	102768	30.41	281.6	5209.3	416.74
AHU10 SF	22	4005	128769	32.15	333.8	7342.5	587.40	3378	108793	32.21	281.5	6193.0	495.44
AHU17 EF	15	3733	92426	24.76	311.1	4666.3	373.30	4235	104789	24.74	352.9	5293.8	423.50
AHU17 SF	22	3878	167081	43.08	323.2	7109.7	568.77	4551	195863	43.04	379.3	8343.5	667.48
AHU18 EF	15	4013	154203	38.43	334.4	5016.3	401.30	4485	172274	38.41	373.8	5606.3	448.50
AHU18 SF	18.5	4037	124523	30.85	336.4	6223.7	497.90	4500	138812	30.85	375.0	6937.5	555.00
CT01 P05	37	660	29147	44.16	55.0	2035.0	162.80	981	44488	45.35	81.8	3024.8	241.98
CT01 P06	37	666	32524	48.83	55.5	2053.5	164.28	931	45941	49.35	77.6	2870.6	229.65
CT02 P07	37	675	33579	49.75	56.3	2081.3	166.50	771	38330	49.71	64.3	2377.3	190.18
CT02 P08	37	0	0	0	0.0	0.0	0.00	1017	51558	50.70	84.8	3135.8	250.86
CT03 P01	37	1410	68708	48.73	117.5	4347.5	347.80	1602	78174	48.80	133.5	4939.5	395.16
CT03 P02	37	1443	70480	48.84	120.3	4449.3	355.94	1467	73961	50.42	122.3	4523.3	361.86
CT04 P03	37	975	43448	44.56	81.3	3006.3	240.50	1239	54926	44.33	103.3	3820.3	305.62
CT04 P04	37	1107	51556	46.57	92.3	3413.3	273.06	720	33874	47.05	60.0	2220.0	177.60
CT05 P09	30	0	0	0	0.0	0.0	0.00	0	0	0	0.0	0.0	0.00
CT05 P10	30	0	0	0	0.0	0.0	0.00	0	0	0	0.0	0.0	0.00
CT06 P11	30	0	0	0	0.0	0.0	0.00	0	0	0	0.0	0.0	0.00
CT06 P12	30	0	0	0	0.0	0.0	0.00	0	0	0	0.0	0.0	0.00

Ops and Energy Results		SEP						OCT					
ASSET	***kW***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***
AHU09 EF	18.5	4230	131515	31.09	352.5	6521.3	521.70	5692	177749	31.23	474.3	8775.2	702.01
AHU09 SF	22	4137	204304	49.38	344.8	7584.5	606.76	5704	277987	48.74	475.3	10457.3	836.59
AHU10 EF	18.5	4497	137685	30.62	374.8	6932.9	554.63	5608	171259	30.54	467.3	8645.7	691.65
AHU10 SF	22	4500	146238	32.50	375.0	8250.0	660.00	5680	184433	32.47	473.3	10413.3	833.07
AHU17 EF	15	4389	109585	24.97	365.8	5486.3	438.90	5969	150406	25.20	497.4	7461.3	596.90
AHU17 SF	22	4593	196775	42.84	382.8	8420.5	673.64	5575	290436	52.10	464.6	10220.8	817.67
AHU18 EF	15	4437	171139	38.57	369.8	5546.3	443.70	5485	211566	38.57	457.1	6856.3	548.50
AHU18 SF	18.5	4443	137906	31.04	370.3	6849.6	547.97	5974	183319	30.69	497.8	9209.9	736.79
CT01 P05	37	1416	63037	44.52	118.0	4366.0	349.28	2844	119773	42.11	237.0	8769.0	701.52
CT01 P06	37	1299	61677	47.48	108.3	4005.3	320.42	636	29860	46.95	53.0	1961.0	156.88
CT02 P07	37	672	33461	49.79	56.0	2072.0	165.76	987	47000	47.62	82.3	3043.3	243.46
CT02 P08	37	330	16275	49.32	27.5	1017.5	81.40	1197	56399	47.12	99.8	3690.8	295.26
CT03 P01	37	1689	78321	46.37	140.8	5207.8	416.62	1488	63213	42.48	124.0	4588.0	367.04
CT03 P02	37	1149	51339	44.68	95.8	3542.8	283.42	2309	98216	42.54	192.4	7119.4	569.55
CT04 P03	37	258	8935	34.63	21.5	795.5	63.64	1011	44105	43.62	84.3	3117.3	249.38
CT04 P04	37	369	16514	44.75	30.8	1137.8	91.02	902	41010	45.47	75.2	2781.2	222.49
CT05 P09	30	0	0	0	0.0	0.0	0.00	135	4382	32.46	11.3	337.5	27.00
CT05 P10	30	0	0	0	0.0	0.0	0.00	264	8746	33.13	22.0	660.0	52.80
CT06 P11	30	0	0	0	0.0	0.0	0.00	234	7495	32.03	19.5	585.0	46.80
CT06 P12	30	0	0	0	0.0	0.0	0.00	54	1749	32.38	4.5	135.0	10.80

Ops and Energy Results		NOV						DEC					
ASSET	***kW***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***	***N***	***Cum. Current (A)***	***Mean. Current (A)***	***Hrs***	***kWh***	***£***
AHU09 EF	18.5	4590	138628	30.20	382.5	7076.3	566.10	3558	107815	30.30	296.5	5485.3	438.82
AHU09 SF	22	4509	219160	48.60	375.8	8266.5	661.32	3495	174077	49.81	291.3	6407.5	512.60
AHU10 EF	18.5	4440	132117	29.76	370.0	6845.0	547.60	3412	101714	29.81	284.3	5260.2	420.81
AHU10 SF	22	4545	146320	32.19	378.8	8332.5	666.60	3445	111873	32.47	287.1	6315.8	505.27
AHU17 EF	15	4254	105249	24.74	354.5	5317.5	425.40	3450	85160	24.68	287.5	4312.5	345.00
AHU17 SF	22	984	55102	56.00	82.0	1804.0	144.32	2559	106518	41.63	213.3	4691.5	375.32
AHU18 EF	15	3207	123669	38.56	267.3	4008.8	320.70	3468	134021	38.65	289.0	4335.0	346.80
AHU18 SF	18.5	4395	134644	30.64	366.3	6775.6	542.05	3462	106497	30.76	288.5	5337.3	426.98
CT01 P05	37	1362	49500	36.34	113.5	4199.5	335.96	831	27812	33.47	69.3	2562.3	204.98
CT01 P06	37	546	21193	38.82	45.5	1683.5	134.68	405	14468	35.72	33.8	1248.8	99.90
CT02 P07	37	300	11872	39.57	25.0	925.0	74.00	291	10032	34.47	24.3	897.3	71.78
CT02 P08	37	603	26092	43.27	50.3	1859.3	148.74	258	9730	37.72	21.5	795.5	63.64
CT03 P01	37	327	9979	30.52	27.3	1008.3	80.66	519	15334	29.55	43.3	1600.3	128.02
CT03 P02	37	1602	57332	35.79	133.5	4939.5	395.16	1206	35769	29.66	100.5	3718.5	297.48
CT04 P03	37	1704	64791	38.02	142.0	5254.0	420.32	1620	51178	31.59	135.0	4995.0	399.60
CT04 P04	37	1587	64452	40.61	132.3	4893.3	391.46	1341	40660	30.32	111.8	4134.8	330.78
CT05 P09	30	2301	74004	32.16	191.8	5752.5	460.20	2318	75046	32.38	193.2	5795.0	463.60
CT05 P10	30	2169	71915	33.16	180.8	5422.5	433.80	2037	67945	33.36	169.8	5092.5	407.40
CT06 P11	30	1923	61770	32.12	160.3	4807.5	384.60	2283	62632	27.43	190.3	5707.5	456.60
CT06 P12	30	2250	72662	32.29	187.5	5625.0	450.00	2028	60157	29.66	169.0	5070.0	405.60

11.8 APPENDIX H: ACCELEROMETER CALIBRATION CERTIFICATE



~ Calibration Certificate ~

Per ISO 16063-21

Model Number: A0322LC-1

Serial Number: P168984

Description: ICP® Accelerometer

L9 ES2 AHV 9

MOTOR NDE

Method: Back-to-Back Comparison AT401-3

Calibration Data

Sensitivity @ 6000 CPM: 100 mV/g (10.2 mV/m/s²)

Output Bias: 11.3 VDC

Sensitivity Plot

Data Points

Frequency (CPM)	Dev. (%)
600	2.4
REF. FREQ.	0.0
60000	-2.2

Condition of Unit

As Found: n/a

As Left: New Unit, In Tolerance

Notes

1. Calibration is NIST Traceable thru Project 683/283498 and PTB Traceable thru Project 10065.
2. This certificate shall not be reproduced, except in full, without written approval from the manufacturer.
3. Calibration is performed in compliance with ISO 9001, ISO 10012-1, ANSI Z540.3 and ISO 17025.
4. See Manufacturer's Specification Sheet for a detailed listing of performance specifications.
5. Measurement uncertainty (95% confidence level with coverage factor of 2) for frequency ranges tested during calibration are as follows: 5-9 Hz; +/- 2.0%, 10-99 Hz; +/- 1.5%, 100-1999 Hz; +/- 1.0%, 2-10 kHz; +/- 2.5%.

Technician: Lamont Langford

Date: 12/12/2014

CSi

835 Innovation Drive
Knoxville, TN 37932
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11.9 APPENDIX I: MONITORING PARAMETERS AND FAULTS (ISO 17359:2011)

Table A.1 — Examples of condition monitoring parameters by machine type

Parameter	Machine type								
	Electric motor	Steam turbine	Aero gas turbine	Industrial gas turbine	Pump	Com-pressor	Electric generator	Reciprocating internal combustion engine	Fan
Temperature	•	•	•	•	•	•	•	•	•
Pressure		•	•	•	•	•		•	•
Pressure (head)					•				
Pressure ratio			•	•		•			
Pressure (vacuum)		•			•				
Air flow			•	•		•		•	•
Fuel flow			•	•				•	
Fluid flow		•			•	•			
Current	•						•		
Voltage	•						•		
Resistance	•						•		
Electrical phase	•						•		
Input power	•				•	•	•		•
Output power	•	•	•	•			•	•	
Noise	•	•	•	•	•	•	•	•	•
Vibration	•	•	•	•	•	•	•	•	•
Acoustic emission	•	•	•	•	•	•	•	•	•
Ultrasonics	•	•	•	•	•	•	•	•	•
Oil pressure	•	•	•	•	•	•	•	•	•
Oil consumption	•	•	•	•	•	•	•	•	•
Oil (tribology)	•	•	•	•	•	•	•	•	•
Thermography	•	•	•	•	•	•	•	•	•
Torque	•	•		•		•	•	•	
Speed	•	•	•	•	•	•	•	•	•
Length		•							
Angular position		•	•	•		•			
Efficiency (derived)		•	•	•	•	•		•	
• Indicates condition monitoring measurement parameter is applicable.									

Table B.2 — Example of electric motor faults matched to measurement parameters and techniques

Machine type: Electric motor	Symptom or parameter change												
Examples of faults	Current	Voltage	Resistance	Partial discharge	Power	Torque	Speed	Vibration	Temperature	Coast down time	Axial flux	Oil debris	Cooling gas
Rotor windings	•				•	•	•	•	•		•		•
Stator windings	•							•	•		•		•
Eccentric rotor	•							•			•		
Brush(es) fault	•	•			•	•			•				
Bearing damage	•					•		•	•	•		•	
Insulation deterioration	•	•	•	•									•
Loss of input power phase	•	•						•			•		
Unbalance								•					
Misalignment								•					
• Indicates symptom may occur or parameter may change if fault occurs.													

Table B.6 — Example of pump faults matched to measurement parameters and techniques

Machine type: Pumps	Symptom or parameter change									
Examples of faults	Fluid leakage	Length measurement	Power	Pressure or vacuum	Speed	Vibration	Temperature	Coast down time	Oil debris	Oil leakage
Damaged impeller		•	•	•	•	•	•	•	•	
Damaged seals	•	•		•	•	•				
Eccentric impeller			•	•	•	•	•	•		
Bearing damage		•	•		•	•	•	•	•	•
Bearing wear		•				•	•	•	•	
Mounting fault						•				
Unbalance						•				
Misalignment		•				•				
• Indicates symptom may occur or parameter may change if fault occurs.										

Table B.10 — Example of fan faults matched to measurement parameters and techniques

Machine type: Fans Examples of faults	Symptom or parameter change Air leakage	Length measurement	Power	Pressure or vacuum	Speed	Vibration	Temperature	Coast down time	Oil debris	Oil leakage
Damaged impeller		•	•	•	•	•	•	•	•	
Damaged oil seals		•		•	•				•	•
Damaged bellows	•									
Eccentric impeller			•	•	•	•	•	•		
Bearing damage		•	•		•	•	•	•	•	•
Bearing wear		•				•	•	•	•	
Mounting fault						•				
Rotor fouled						•				
Unbalance						•				
Misalignment		•				•				

• Indicates symptom may occur or parameter may change if fault occurs.